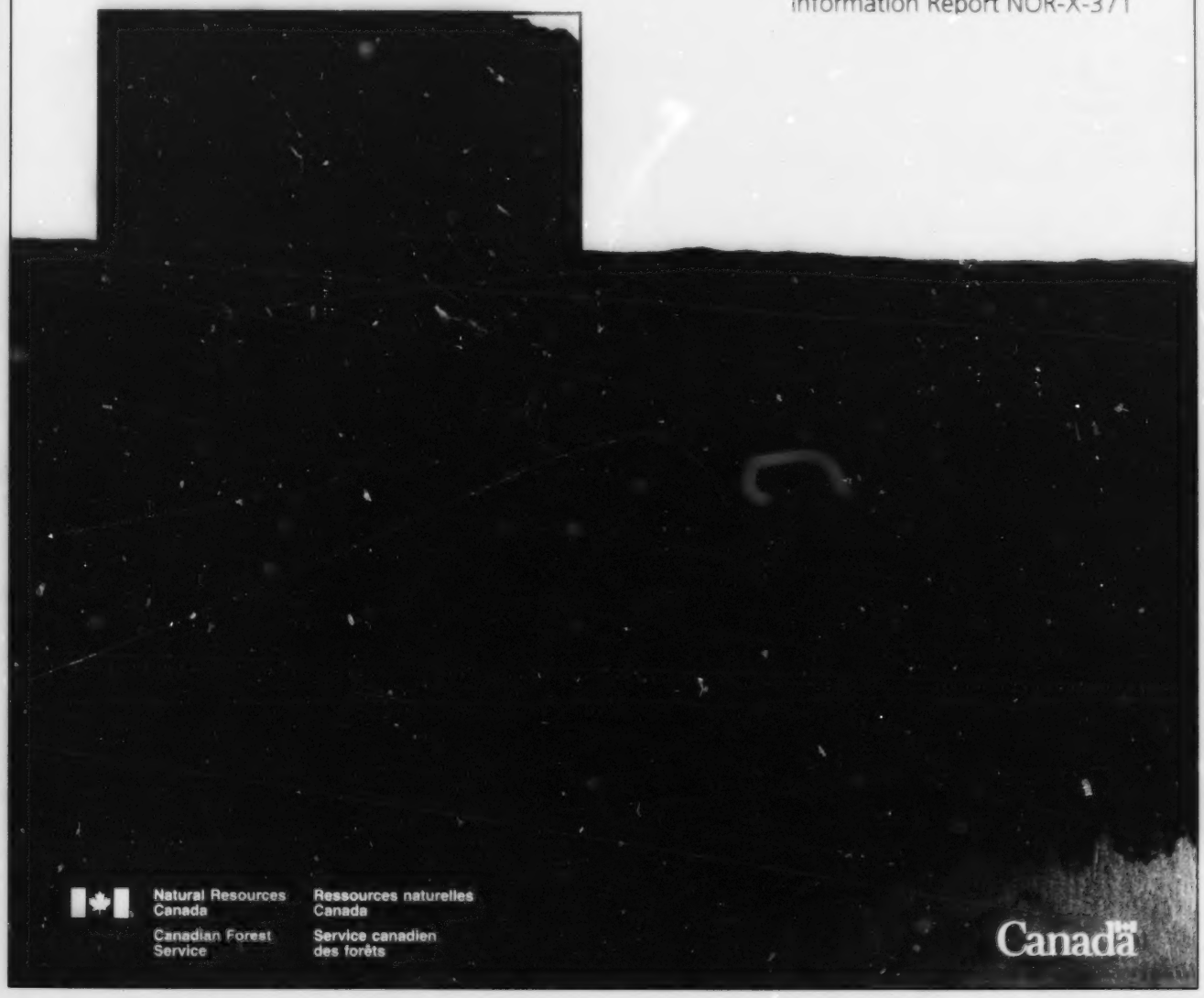
Landscape fire modeling—challenges and opportunities

B.C. Hawkes and M.D. Flannigan, editors

Northern Forestry Centre
Information Report NOR-X-371



Natural Resources Canada
Canadian Forest Service

Ressources naturelles Canada
Service canadien des forêts

Canada

The Canadian Forest Service's Northern Forestry Centre is responsible for fulfilling the federal role in forestry research and technology transfer in Alberta, Saskatchewan, Manitoba, and the Northwest Territories. The main objectives are research in support of improved forest management for the economic, social, and environmental benefit of all Canadians.

The Northern Forestry Centre is one of five centers of the Canadian Forest Service, which has its headquarters in Ottawa, Ontario.

Le Service canadien des forêts, Centre de foresterie du Nord, représente le gouvernement fédéral en Alberta, en Saskatchewan, au Manitoba et dans les Territoires du Nord-Ouest en ce qui a trait aux recherches forestières, et au transfert de technologie. Cet organisme s'inté esse surtout à la recherche en vue d'améliorer l'aménagement forestier afin que tous les Canadiens puissent en profiter aux points de vue économique, social et environnemental.

Le Centre de foresterie du Nord constitue l'un des cinq établissements du Service canadien des forêts, dont l'administration centrale est à Ottawa (Ontario).

Cover photo:

Agnes Lake Fire south of Lesser Slave Lake, Alberta, 1998 (photo by Brian Amiro, Canadian Forest Service). **Inset:** A FARSITE fire growth simulation model output showing a fire in the Bitterroot Valley of Montana (provided by Mark Finney, USDA Forest Service).

102-03268/

LANDSCAPE FIRE MODELING—CHALLENGES AND OPPORTUNITIES

B.C. Hawkes[1] and M.D. Flannigan, editors

Proceedings of the
Landscape Fire Modeling Workshop
Victoria, British Columbia
November 15–16, 1999

INFORMATION REPORT NOR-X-371

Canadian Forest Service
Northern Forestry Centre
2000

[1] Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia V8Z 1M5

© Her Majesty the Queen in Right of Canada, 2000
Catalogue No. Fo46-12/371E
ISBN 0-662-29253-7
ISSN 0704-7673

This publication is available at no charge from:

Natural Resources Canada
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton, Alberta T6H 3S5

A microfiche edition of this publication may be purchased from:

Micromedia Ltd.
240 Catherine Street, Suite 305
Ottawa, Ontario K2P 2G8

CANADIAN CATALOGUING IN PUBLICATION DATA

Landscape Fire Modeling Workshop (Victoria, B.C. ; 1999)

Landscape fire modeling—challenges and opportunities : proceedings of the Landscape Fire Modeling Workshop, Victoria, British Columbia, November 15–16, 1999

(Information report ; NOR-X-371)
Includes an abstract in French.
Includes bibliographical references.
ISBN 0-662-29253-7
Cat. no. Fo46-12/371E

1. Forest fires — Simulation methods — Congresses. 2. Forest fire forecasting — Simulation methods — Congresses. I. Hawkes, B.C. (Brad C.). II. Flannigan, M.D. (Michael Donald). III. Northern Forestry Centre (Canada). IV. Title. V. Series: Information report (Northern Forestry Centre) ; NOR-X-371.

SD421.34L26 2000 634.9'618'011 C00-980353-X

This report has been printed on Canadian recycled paper.

Hawkes, B.C.; Flannigan, M.D., editors. 2000. *Landscape fire modeling—challenges and opportunities. Proc. Landscape Fire Modeling Workshop, November 15–16, 1999, Victoria, B.C.* Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-371.

ABSTRACT

The Landscape Fire Modeling Workshop was held on November 15–16, 1999 at the Pacific Forestry Centre, Victoria, British Columbia. Sixteen papers were presented on opportunities associated with and limitations of landscape fire models for boreal and temperate ecosystems. Specific topics included modeling gaps and needs, application of fire models for forest and vegetation management, and future directions. Summaries from the breakout sessions are also included in this report.

RÉSUMÉ

Un atelier sur la modélisation des incendies à l'échelle du paysage s'est déroulé les 15 et 16 novembre 1999 au Centre de foresterie du Pacifique, à Victoria, en Colombie-Britannique. Il a donné lieu à la présentation de 16 communications sur les possibilités et les limites inhérentes aux modèles des incendies à l'échelle du paysage dans les écosystèmes boréaux et tempérés. Au nombre des sujets particuliers abordés figurent les lacunes et les besoins en matière de modélisation, les applications des modèles des incendies en aménagement forestier et en gestion de la végétation et les orientations futures. Le rapport présente également des résumés des travaux des groupes de discussion.

CONTENTS

Fire Effects at Landscape Scales – *Robert H. Gardner* 1

Overview of Dynamic General Vegetation Models – *Ronald P. Neilson, James M. Lenihan, and Dominique Bachelet* 3

Landscape Fire Succession Modeling: Linking Ecosystem Simulations for Comprehensive Applications – *Robert E. Keane* 5

Canadian Forest Service Perspectives and Vision of Landscape Fire Modeling – *Sylvie Gauthier* 9

Fire Impact Management – *David L. Martell* 11

Applications in Forest and Vegetation Management—Alberta's Perspective – *Cordy Tymstra* 13

Description and Uses of FARSITE – *Mark A. Finney* 16

Exploring Possibilities in Nature using LANDMINE – *David W. Andison* . . . 18

Spatial Fire Regime Simulation in a Spatially Explicit Model for Landscape Dynamics (SEM-LAND) – *Chao Li* 20

TELSA: the Tool for Exploratory Landscape Scenario Analyses – *Werner A. Kurz, Sarah J. Beukema, and Walt Klenner* 21

Multiscale Models of Fire in Boreal Forests – *Steve Cumming* 23

LAMOS: a LAndscape MOdelling Shell – *Sandra Lavorel, Ian D. Davies, and Ian R. Noble* 25

Exploring the Envelope of Variation with LANDIS, a Spatially Explicit Model of Forest Disturbance and Succession – *Frédérik Doyon* 29

Toward a Language for General Fire Modeling – *Andrew Fall* 30

Simulating fire regimes with FIRESCAPE – *Geoffrey J. Cary* 32

A Regional-Scale Fire Model for a Dynamic Global Vegetation Model – *Sergey Venevsky, Kirsten Thonicke, Stephen Sitch, and Wolfgang Cramer* 34

Break-Out Sessions 36
1. Incorporating Fire into Dynamic Global Vegetation Models 36
2. Gaps and Information Needs in Fire Models 38
3. Application of Fire Models with Respect to Forest and Vegetation Management 39
4. Questions for Future Landscape Fire Models 42

Summary 44

Participant List 45

Note

The views, conclusions, and recommendations published in this proceedings are those of the authors and do not necessarily imply endorsement by the Canadian Forest Service.

The exclusion of certain manufactured products does not necessarily imply disapproval nor does the mention of other products imply endorsement by the Canadian Forest Service.

Preface

The following special report features abstracts by the keynote speakers and fire-model presenters at the Landscape Fire Modeling Workshop, which was held at the Pacific Forestry Centre, Victoria, British Columbia, November 15–16, 1999. Summaries from the breakout sessions are also included in this report. This workshop was sponsored by the Canadian Forest Service, the Climate Change Action Fund, and the Global Change Terrestrial Ecosystems Programme.

This workshop explored opportunities associated with and limitations of landscape fire models for boreal and temperate ecosystems. Participants from around the world and from diverse backgrounds came to learn more about landscape fire modeling. Specific topics include modeling gaps and needs, application of fire models for forest and vegetation management, and future directions.

This workshop was one of the planned regional workshops in the development of a fire module to be used in dynamic global vegetation models. This global model is being developed as part of the efforts of the Global Change Terrestrial Ecosystems group, which is part of the International Geosphere–Biosphere Programme: A Study of Global Change.

Fire Effects at Landscape Scales

Robert H. Gardner
Appalachian Environmental Laboratory, University of Maryland Center for Environmental Studies
301 Braddock Road, Frostburg, Maryland, USA 21532
E-mail: gardner@al.umces.edu

Many regions of the world are experiencing rapid changes in the diversity and structure of forests as a consequence of landscape change and altered fire regimes (e.g., frequency, severity, and extent of fires). Current understanding and projections of these effects are based on a variety of studies. Many empirical studies have evaluated contemporary changes over 100 years or so, and a limited number of studies have used dendrochronology and reconstructed stand histories to create records for periods longer than 800 years. These studies are critical for establishing relationships among weather, fuels, and fire, but simulation models are still necessary to evaluate future changes in fire regimes due to shifts in climate and the subsequent changes in the landscape patterns of forested areas.

A comparison of a broad range of model types provides insight into the methods used to establish relationships among fire, fire effects, and the recovery of disturbed areas and the general conclusions of these studies. Such a comparison yields the following conclusions.

1) Simple theoretical models of fire-prone forests show that these landscapes can demonstrate properties of self-organization wherein the continuity of fuels is often sufficient to sustain very large fires.

2) The property of self-organization allows scaling rules to be developed to extrapolate from the fine-grained structure of fuels and fire to much broader temporal and spatial scales.

3) The frequent shifts in species composition, community structure, and ecosystem dynamics due to fires mean that landscape patterns are unlikely to ever be in a state of equilibrium. Therefore, coupling ecosystem models with simulations of fire disturbance deserves much more attention.

4) Small shifts in climate can produce dramatic shifts in the fire regime, with subsequent changes in the age structure and the spatial arrangement of the mature forest.

5) The high level of uncertainty associated with the dynamics of a disturbed system and the lack of understanding of processes operating at landscape scales mean that models should be compared and used to generate projections, with results expressed in terms of risk of change.

Unfortunately, all models are simple representations of complex systems. Therefore, we can expect them to be imperfect representations of the multitude of factors that might be important in predicting landscape-scale patterns of fire disturbance. For instance, the process of fire-spotting remains poorly understood and is infrequently included in fire models; the dynamics of winds during fire events are difficult to quantify in space and time, which makes the scale-dependence of their effects difficult to evaluate; the description of the spatial heterogeneity of fuels, fuel moisture, and weather remains coarse and uncertain; and factors contributing to changes in land use are usually neglected. The inclusion of realistic dynamics of forest regrowth and succession, as well as the coupling of community and ecosystem dynamics, has only recently been attempted. These methods need to be expanded to cover a broader spectrum of forest types and climatic zones.

The inclusion of additional variables would serve to greatly increase the complexity of current models. However, there are clear dangers to increasing model complexity, in part because the uncertainties associated with these details may overwhelm the reliability of a model's predictions. The additional complexity makes the process of model verification more difficult, and the addition of unknowns may increase the bias associated with predictions. There are, however, corresponding dangers in the

exclusive use of simple models. Key processes that affect both fine-grained dynamics and broad-scale trends may be absent from simple models unless models and data are systematically compared. Although this problem is an old and familiar one, these issues are only now being considered for disturbance models that make predictions over broad temporal and spatial scales.

There are three suggestions to resolve some of these difficulties. First, the results of model simulations are simply the logical consequences of a series of hypotheses and assumptions. The relevant question is, how different would the projections be if one or more assumptions were relaxed, if different processes were included or disregarded, or if an alternative set of hypotheses were tested? This question can best be evaluated by cross-comparison of model sensitivities with relevant empirical studies and the quantification of differences in response between models. Second, there must be a renewed effort to develop simple yet reliable models for extrapolation of results across scales. Rigorous sets of model experiments are necessary to estimate the errors and uncertainties associated with cross-scale predictions. If scaling rules can be developed for complex models, then the effects of climate change (which act at broad scales) might be revealed in changes in disturbance regimes and corresponding shifts in forest structure. Finally, the study of fire in natural systems must be expanded to include systems altered by changes in land use. In many regions of the world, changes in agricultural practices are increasing the risk of fire, whereas in other regions, forest fragmentation is reducing the risk of large fires. These shifts in land use confound the estimates of net carbon storage and nutrient release as a result of forest disturbance.

Overview of Dynamic General Vegetation Models

Ronald P. Neilson
USDA Forest Service, Forest Sciences Laboratory
3200 SW Jefferson Way, Corvallis, Oregon, USA 97331
E-mail: neilson@fsl.orst.edu

James M. Lenihan
Forest Sciences Laboratory, Oregon State University
3200 SW Jefferson Way, Corvalis, Oregon, USA 97331
E-mail: lenihan@fsl.orst.edu

Dominique Bachelet
Forest Sciences Laboratory, Oregon State University
3200 SW Jefferson Way, Corvalis, Oregon, USA 97331
E-mail: bachelet@fsl.orst.edu

Dynamic general vegetation models (DGVMs) represent a relatively new technology and exist in several different varieties. Two broad classes are process-based and statistical–empirical. This discussion will focus on the first of these. Among process-based models there is also a variety of approaches, which range from more to less process-based in many of their details. In general, DGVMs are constructed from two primary components, a biogeography model and a biogeochemistry model. Usually, these are also accompanied by some sort of fire disturbance model. The biogeochemistry of different DGVMs is roughly similar with respect to soil organic matter and nitrogen processes, often being adapted from the CENTURY algorithms. Canopy processes are either process-based, using some variation of the Farquhar photosynthesis scheme, or empirical, as in the CENTURY model. We have constructed two DGVMs within the MAPSS team, which typify the range from process-based to more empirical approaches.

There are three broad, interrelated challenges when constructing a DGVM: accurately representing the process and the ecosystem structure, accounting for sub-grid-cell spatial heterogeneity, and accounting for temporal heterogeneity, specifically disturbance and succession. Most DGVMs adopt a "savanna" structure. That is, they consist of a woody overstory competing with an ephemeral understory, usually over a multilayered soil. Closed forests and open grasslands are special cases of the savanna structure allowing one model structure to simulate all vegetation types. However, different models represent savanna processes differently. Our models, MC1, a MAPSS–CENTURY hybrid, and BIOMAP, a MAPSS–BIOME–BGC hybrid, typify two different approaches to the savanna structure. CENTURY was brought to the linkage with a savanna structure intact. However, the competition processes are fairly empirical. For example, water competition is simulated through an indexed modulation of productivity based on soil water content. Transpiration is not differentiated among life-forms. BIOME–BGC, however, is a model with one life-form and one soil layer. We generalized the BIOME–BGC structure to mimic that of MAPSS, with an overstory competing with an understory over multiple soil layers. There can be multiple life-forms in each of the two canopy layers, each with different rooting depths Competition is based on the Beer's law light extinction process and on differential uptake of water from the various soil layers according to canopy demand for transpiration from each life-form, the density of fine roots in each soil layer, and the availability of water in each layer. Thus, water competition is a direct result of differential rates of water uptake from a common reservoir, where roots overlap in vertical distribution. We have found that the mathematical form of competition and other fundamental plant processes, for example the formulation for transpiration, can affect the emergent property of vegetation biogeography, that is, the locations and orientation of major ecotones.

Spatial heterogeneity has so far only been accommodated by increasing the grid-cell resolution while treating each cell as a homogenous entity. This approach to spatial heterogeneity works well

enough for equilibrium models but presents problems with DGVMs. Even so, grid cells with substantial topo-edaphic heterogeneity are represented as some average vegetation type, which may not exist to any large extent in the cell. For example, a grid cell dominated by north- and south-facing slopes may be populated by forests and grasslands on the two aspects, respectively. However, an average grid cell simulation may produce a savanna. Still, the most significant difficulties arise with respect to the third challenge, temporal heterogeneity.

Vegetation change occurs through the death and replacement of individuals by new individuals of a different species or life-form and through the process of succession, as captured by the classical gap model paradigm. Usually, succession to new species is initiated by some disturbance, be it merely a single tree falling down, as in gap-phase succession, or a more catastrophic disturbance, such as fire, insects, or diseases. These disturbance processes invariably occur at the sub-grid cell level over most grids used by DGVMs, which range from about 10 km to about 50 km in resolution. There are two related problems with temporal heterogeneity. One is the proliferation of distinct age classes within a grid cell due to the processes of disturbance. The other is the gradual replacement of one life form type by another either through normal succession or because of directional climatic change. Life-form mixtures from either process are difficult to render in DGVMs. MC1 and BIOMAP accommodate these challenges in very different ways. Fire is currently the only disturbance available for either DGVM. Fire area is calculated for each fire, so the fraction of the cell that is disturbed can be calculated. Fire would normally result in the creation of a new age class with very different structural and successional states than neighboring terrain within the same grid cell. However, MC1 currently distributes the impact of fire over the entire grid cell, after calculating the magnitude of impact for the specific area that has been disturbed. This dilutes the effect and no doubt creates some error in the future simulated trajectory of the cell. One design for the next generation of DGVMs will keep track of the area of unique age classes. New age classes will be created with each disturbance. However, as they age, their state characteristics become increasingly similar and they will eventually merge.

Succession from one life-form type to another, for example, from conifer to broadleaf, presents similar difficulties. The challenge is to represent changing mixtures over time, while keeping track of the allometric characteristics of the biomass and carbon pools. Again, the approaches taken in MC1 and BIOMAP are quite different. Life-form type is determined in MC1 by a series of rules similar to those in the original MAPSS model. However, the climate envelopes defining the life-form types occur along gradients of temperature and rainfall variables, allowing gradual transitions or mixtures between various types. Parameter values defining each life-form are gradually varied along the transitional gradients to represent the changing functional responses of the shifting life-form mixtures. The structure of BIOMAP allows explicit mixtures of different life-forms, much as in a gap model, with competition among life-forms for light, water, and nutrients. The climate-based life-form rules will determine which new life-forms can enter a site after disturbance. However, competition will drive succession and variation in life-form mixtures thereafter. Accurate successional progression to potential climatic climax depends on how well the core processes are captured.

Fire is the only explicit disturbance currently simulated in DGVMs. Both process-based and empirical approaches are being used. A statistical approach is used in LPJ, a DGVM extended from BIOME3. The approach relies on the historical fire-return interval for different vegetation types, but fire ignition and intensity can be modulated by climate variables. MC1 uses a process-based approach, incorporating the Rothermel ground fire model and the VanWagner crown fire model. Fuel loadings and moisture levels are taken from the DGVM output, and ignition is based on critical loadings and moisture levels to both ignite a fire and carry it to a substantial size. Specific fractions of biomass consumed are calculated for the canopy, boles, roots, and litter of different size classes. The MC1 fire model has qualitatively simulated the large fires of 1910 in the west, the 1988 Yellowstone fires, and many others during the past century, but specific precision has yet to be tested.

The DGVMs are unique tools for examining vegetation change under changing climate and disturbance. However, they are very new and much remains to be incorporated. Apart from simple shakedown and improvement of existing processes, perhaps the next most important challenge will be the incorporation of dynamic land-use change, in terms of both historical and potential future management practices.

Landscape Fire Succession Modeling: Linking Ecosystem Simulations for Comprehensive Applications

Robert E. Keane
USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory
P.O. Box 8089, Missoula, Montana, USA 59807
E-mail: rkeane@fs.fed.us

Introduction

Wildland fire is a critical disturbance process in many ecosystems worldwide, yet it is difficult to study fire and its effects across large landscapes over long periods. Most field studies evaluate the effect of fire only at the stand level, usually after only one fire event. Simulation modeling provides an alternative approach for investigating cumulative fire effects across most ecosystem components in large spatial and temporal domains. Simulation modeling probably should not be a research end in itself, but instead it can provide a means to efficiently design and conduct future field studies to verify model results and obtain new information to refine old models and build new ones.

Landscape fire succession modeling is the simulation of the interaction of wildland fire with ecosystem processes, especially vegetation development, at the landscape scale. Many approaches are used to develop all or parts of fire succession simulation models, and they are usually categorized into four groups. With an empirical approach statistical relationships derived from actual data drive the model. Deterministic approaches use generalized functions to represent the complex relationships that drive simulation dynamics. Stochastic models use probability distributions to represent primary ecosystem processes over time and space. Lastly, mechanistic models use fundamental physical relationships to simulate the underlying processes or causal mechanisms that dictate system behavior (Gay 1989). All of these models have various advantages and disadvantages, and it seems that the best computerized fire succession models often use combinations of all four approaches. The challenge in simulating fire and succession across landscapes is to link relevant approaches to match model scale and application. Empirical, deterministic, stochastic, and mechanistic approaches can be used to develop and link fire succession submodels, but it is important that temporal and spatial scale, and application of the model, be taken into account.

Fire succession modeling must incorporate multiple-scale simulation. This paper will discuss the components needed to simulate fire succession at the landscape and stand scales. Then, the most important processes needed to model fire succession are presented for these two scales.

Landscape Processes

There are essentially four major processes that affect fire successional processes at the landscape scale: climate, fire, seed dispersal, and hydrology. These processes act across all organizational scales, and it is difficult to link their effects to ecosystems as their simulation progresses across scales. Land-use activities, such as forestry practices, human settlement, grazing, and fire suppression, are important disturbance processes that affect fire regime and landscape structure. Unfortunately, limited space prevents a thorough discussion of human impacts on fire dynamics. Insects and diseases are also important disturbance processes on the landscape, and their simulation should be included in a fire succession model. Especially important is the interrelationship of insect, climate, and fire regimes. However, a review of insect and disease simulation methods is beyond the scope of this discussion.

Climate and Weather

Climate is integral to any simulation of fire and succession, because it plays a critical role across all ecosystems and their components every day. The temporal expression of climate at the biophysical setting and stand level is referred to here as weather. Climate and weather are important at the coarse scale for ecosystem processes such as species distributions, hydrologic cycles, and fire regimes; at the midscale for plant growth, decomposition, and fire patterns; and at the fine scale for

plant regeneration, mortality, and fire spread. Conversely, the effect of fire on landscape structure and composition can influence regional climate and weather (Pielke and Avissar 1990; Segal et al. 1988).

Fire

The simulation of fire across multiple scales requires at least two modules. First, a fire ignition module is needed to start a fire on the landscape, and then a fire growth module is needed to spread that fire across the landscape. These two modules must be linked in space and time to the landscape and climate components for realistic simulations. This is an extremely difficult task because a mechanistic fire ignition module will require daily or hourly weather data from century-long records across an entire landscape, defined at a resolution fine enough to distinguish lightning strikes on fuel beds. A detailed mechanistic fire growth model also requires hourly weather data and high-resolution spatial data layers that define fuel characteristics, topography, and vegetation. Obviously, a compromise must be reached between model resolution and algorithm realism, given the state of available research and current computer technology. Hopefully, future computer systems will be able to handle the billions of instructions needed to mechanistically simulate fire ignition and growth for research and management applications.

Fire Ignition Module

Perhaps the most difficult and least understood challenge in any fire simulation is predicting when and where a fire will actually start on the landscape. Ignitions caused by people can be relatively easy to model using a stochastic approach that is dependent on Julian date and distance from developed areas (Vega Garcia et al. 1995; Martell et al. 1989). However, natural ignitions, especially those from lightning, are much more difficult to simulate using a mechanistic approach because their prediction requires extensive, accurate data concerning lightning dynamics, ignition processes, smoldering processes, and combustion physics.

Fire Growth Simulation

There are many fire behavior simulation models available for research and management applications, but only a few would be compatible with fire succession design. Fire growth models can be grouped by mechanistic and nonmechanistic approaches in a spatial or nonspatial implementation. Mechanistic, nonspatial models developed by Albini (1976), Rothermel (1972, 1991), McArthur (1967), Nobel et al. (1980) and the Forestry Canada Fire Danger Group (1992) are used extensively in land and fire management programs around the world. Computer programs of these models, such as BEHAVE (Andrews 1986), are the backbone of many fire management programs. Nonspatial models with empirical approaches include the model by Nobel et al. (1980) and, for Canada, the model developed by the Forestry Canada Fire Danger Group (1992). Although these models are not as robust and sometimes have only local applications, they are useful because they require minimal inputs and generate relatively accurate predictions.

Seed Abundance and Dispersal

Seed crop abundance and dispersal are critical processes needed to simulate the migration of plant species across a landscape. The amount and distribution of plant propagules across landscapes play important roles in postfire successional dynamics and subsequent landscape composition and structure. Seed crop is a difficult process to model because it depends on many cross-scale factors, including species, plant health, long-term weather trends (e.g., drought), short-term weather disturbances (e.g., winds, hail storms, early frosts), and animal predation (Eis and Craigdallie 1983; Shearer 1985). The frequency and intensity of seed crops is usually simulated by species at the landscape level with stochastic approaches, for which probabilities of seed crop classes (e.g., good, fair, and poor) are taken from field studies (Keane et al. 1989; Kercher and Axelrod 1984). Mechanistic approaches may become possible as ecophysiological research efforts quantify the relationships between plant carbon allocation to reproductive organs and the native environment (Landsberg and Gower 1997).

Hydrologic Processes

The routing of water as it flows across the landscape is a critical link to stand-level water cycling, which may determine unique vegetation compositions and moisture conditions for specific areas in the landscape. Many hydrologic models have been developed with various approaches for diverse purposes. The selection of which hydrologic routing model to include in fire succession models ultimately depends on modeling objectives and available resources, since any spatially explicit simulation of hydrology requires additional computer resources and expertise. If riparian stand dynamics or fire's effect on stream flow is of concern, then a detailed representation of hydrologic processes should be included. A simple

and less comprehensive hydrologic routing module might be suitable if only upland stand dynamics are important. However, detailed, physically based hydrology models have many parameters that require intensive quantification and calibration, and model outputs can have a high level of predictive uncertainty (Binley et al. 1991).

Stand Processes

Fire succession modeling must include specific model components and compartments at the stand and organism simulation level to achieve the stated objective of exploring fire's role in landscape ecology. Vegetation, fuels, and soil must be defined by an appropriate set of compartments that allow the application of model results to management issues and research problems. The level of stratification of these components again depends on the objective of the simulation and the desired outputs. Plant growth, regeneration, and mortality must be comprehensively simulated from climate drivers using mechanistic approaches linked to landscape-level component results (Landsberg and Gower 1997). The cycling of organic matter and nutrients must be explicitly modeled from the processes of plant litter fall, atmospheric deposition, and decomposition (Waring and Schlesinger 1985). The effect of fire on the abiotic and biotic components of the stand and organism must also be included in module design. Presented here is the proposed structure of compartments for simulating ecosystem dynamics at the stand and organism scale needed for developing fire succession models.

Ecosystem Dynamics Modeling

Ecosystem models or succession drivers can be classified into combinations of four categories: stand-level or plant-level, stand-based or plant-based, mechanistic or nonmechanistic, and spatial or nonspatial. A stand-level model simulates all ecosystem processes across a homogeneous piece of ground, whereas a plant-level model simulates the dynamics of only one plant. Plant-level models are difficult to scale up to the stand level because of their inherent complexity and detail. Stand-based models simulate stand characteristics as one entity instead of as a collection of individual plants. For example, many growth and yield models used in forestry simulate changes in stand basal area over time. Plant-based models simulate interactions between individual plants and their environment within a stand to investigate ecosystem dynamics. Mechanistic models attempt to simulate basic biogeochemical processes from fundamental physical relationships and relate them to ecosystem dynamics. Ecosystem models that directly simulate spatial interactions are called spatial models. A summary of these models is provided by Hunsaker et al. (1993) and Baker (1989). Only stand-based, stand-level, and plant-level mechanistic models are appropriate for inclusion in a fire succession model.

Fire Effects

Most fire effects are directly computed at the stand and organism level in the fire succession model, and these results usually translate upward in scale to incur significant landscape-level effects. It is impossible to simulate the full extent of fire's influence on all ecosystem components because of the complexity of fire processes and the lack of field studies that take a comprehensive approach to the evaluation of fire effects. Most research efforts study only one aspect of fire's aftermath, such as fuel consumption, and do not link that effect to changes in ecosystem processes across spatial and temporal scales. Currently, there are five major fire effects that, at a minimum, should be included in designing fire succession models—fuel consumption, plant mortality, soil heat pulse, smoke, and nutrient cycling. Other, second-order fire effects, such as soil erosion, are important but can be added to a fire succession model as needed and will not be discussed here.

Implementing Fire Succession Models

The complexity and detail involved in developing a fire succession model with a totally mechanistic approach would ultimately prevent its construction. However, it is possible to create a spatially explicit landscape fire model using parts or simplifications of the approaches presented here. Empirical and stochastic modules can be substituted for some mechanistic components until adequate research and computer technology become available. Our research group has several recommendations for the successful construction of such a model. First, it is imperative that the simulation objectives be clearly defined before construction so that appropriate modules can be designed and included in the model structure. Model-building is more focused and efficient when specific simulation objectives are used as guidelines (Korzukhin et al. 1996). Second, it is more efficient if the model is constructed from a set of linked computer programs that can be easily added or removed from the simulation, like building blocks or Tinkertoys (Bevins and Andrews 1994). Comprehensive simulation of ecosystem processes and their interactions

is an extremely complex task, and the development of detailed mechanistic models to simulate these processes is often best left to the appropriate discipline. Many of the same routines are reprogrammed by modelers for different ecosystem modeling projects, and each version is different. It may be more practical if simulation modules are simply taken from previously tested models and modified for inclusion in linked fire simulations. Lastly, there must be comprehensive verification and testing of intermediate and final simulation results to assess model behavior, sensitivity, accuracy, and precision (Rastetter 1996). This requires extensive field data sets to validate internal algorithms and parameters so that simulation computations can be interpreted in the right context (Turner et al. 1989).

References

Albini, F.A. 1976. Computer-based models of wildland fire behavior: a user's manual. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, UT.

Andrews, P.L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system—BURN subsystem. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, UT. Gen. Tech. Rep. INT-194.

Baker, W.L. 1989. A review of models of landscape change. Landsc. Ecol. 2(2):111–133.

Bevins, C.D.; Andrews, P.L. 1994. The Loki software architecture for fire and ecosystem modeling: a tinker toy approach. Pages 252–260 *in* Proc. 12th Int. Conf. Fire For. Meteorol., October 26–28, 1993, Jekyll Island, GA. Soc. Am. For., Bethesda, MD.

Binley, A.M.; Beven, K.J.; Calver, A.; Watts, L.G. 1991. Changing responses in hydrology: assessing the uncertainty in physically based model predictions. Water Resour. Res. 27(6):1253–1261.

Eis, S.; Craigdallie, D. 1983. Reproduction of conifers: a handbook for cone crop assessment. Can. For. Serv., Ottawa, ON. For. Tech. Rep. 31.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. For. Can., Ottawa, ON. Inf. Rep. ST-X-3.

Gay, C.A. 1989. Modeling tree level processes. Pages 143–155 *in* R.D. Noble, J.L. Martin, and K.F. Jensen, eds. Proc. 2nd US–USSR Symp. Air Pollution Effects on Vegetation Including Forest Ecosystems, September 1988, Corvalis, OR. U.S. Dep. Agric., For. Serv., Northeastern For. Exp. Stn., Broomall, PA.

Hunsaker, C.T.; Nisbet, R.A.; Lam, D.C.; Brower, J.A.; Baker, W.L.; Turner, M.G.; Botkin, D.B. 1993. Spatial models of ecological systems and processes: the role of GIS. Pages 248–264 *in* M.F. Goodchild, B.O. Parks; and L.T. Steyaert. Environmental modeling with GIS. Oxford Univ. Press, New York, NY.

Keane, R.E.; Arno, S.F.; Brown, J.K. 1989. FIRESUM—an ecological process model for fire succession in western conifer forests. U.S. Dep. Agric., For. Serv., Intermt. Res. Stn., Ogden UT. Gen. Tech. Rep. INT-266.

Kercher, J.R.; Axelrod, M.C. 1984. A process model of fire ecology and succession in a mixed-conifer forest. Ecology 65(6):1725–1742.

Korzukhin, M.D.; Ter-Mikaelian, M.T.; Wagner, R.G. 1996. Process versus empirical models: which approach for forest ecosystem management? Can. J. For. Res. 26:879–887.

Landsberg, J.J.; Gower, S.T. 1997. Applications of physiological ecology to forest management. Acad. Press, San Diego, CA.

Martell, D.L., Bevilacqua, E.; Stocks, B.J. 1989. Modelling seasonal variation in daily people-caused forest fire occurrence. Can. J. For. Res. 19:1555–1563.

McArthur, A.G. 1967. Fire behavior in eucalypt forests. Commonw. Aust. For. Timber Bur. Leafl. 107.

Nobel, I.R.; Bary, G.A.V.; Gill, A.M. 1980. McArthur's fire danger meters expressed as equations. Aust. J. Ecol. 5:201–203.

Pielke, R.A.; Avissar, R.A. 1990. Influence of landscape structure on local and regional climate. Landsc. Ecol. 4:133–155.

Rastetter, E.B. 1996. Validating models of ecosystem response to global change. Bioscience 46(3):190–197.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, UT. Res. Pap. INT-115.

Rothermel, R.C. 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains. U.S. Dep. Agric., For. Serv., Intermt. Res. Stn., Ogden, UT. Res. Pap. INT-438.

Segal, M.; Avissar, R.; McCiumber, M.C.; Pielke, R.A. 1988. Evaluation of vegetation effects on the generation and modification of mesoscale circulation. J. Atmos. Sci. 45:2268–2292.

Shearer, R.C., comp. 1985. Cone production on Douglas-fir and western larch in Montana. Pages 63–68 *in* Conifer Tree Seed in Inland Mountain West Symp., August 5–6, 1985, Missoula, MT. U.S. Dep. Agric., For. Serv., Intermt. Res. Stn., Ogden, UT.

Turner, M.G.; Costanza, R.; Sklar, F.H. 1989. Methods to evaluate the performance of spatial simulation models. Ecol. Model. 48:1–18.

Vega Garcia, C.V.; Woodard, P.M.; Titus, S.J.; Adamovicz, W.L.; Lee, B.S.; 1995. A logit model for predicting the daily occurrence of human-caused forest fires. Int. J. Wildland Fire 5(2):101–111.

Waring, R.H.; Schlesinger, W.H. 1985. Forest ecosystems concepts and management. Acad. Press, San Diego, CA.

Canadian Forest Service Perspectives and Vision of Landscape Fire Modeling

Sylvie Gauthier
Laurentian Forestry Centre, Canadian Forest Service
P.O. Box 3800, 1055, rue du P.E.P.S., Sainte-Foy, Québec, Canada G1V 4C7
E-mail: sgauthier@cfl.forestry.ca

From the standpoint of the Canadian Forest Service, there are four main areas where landscape fire modeling is required: in the development and assessment of sustainable forest management (SFM) strategies, in the evaluation of fire effects and postfire system recovery, in assessing the degree of change in Canadian forests with respect to the forecast climate change, and, finally, in fire protection and fire management. My perspective as a nonmodeler is that these four areas address different problems at different spatiotemporal scales, and therefore the modeling efforts require different levels of precision in terms of fire modeling at the landscape level.

Development and Assessment of SFM Strategies

Age structure and stand composition of forest mosaics are clearly identified as indicators of SFM in the documents of the Canadian Council of Forest Ministers. Maintaining forest-mosaic diversity (in terms of age-class distribution and habitat types) in managed systems similar to that observed in the natural landscape is often proposed as a coarse-filter strategy to minimize the risk of losing important components of biodiversity (Hunter 1990, 1993). The current stand composition of a natural forested landscape reflects the response of forest cover to interactions between physical determinants (e.g., climate, topography, and surficial geology) and the disturbance regime associated with each region. The development of a coarse-filter approach in a managed landscape requires knowledge of the historical range of variation in disturbance regimes and its relationship to forest composition features. Landscape fire models are needed to assess this temporal variation.

Model Characteristics

- Regional landscape level (strategic simulation model).
- Time frame: centuries.
- Need to evaluate variability (in terms of stand age, patch size, and successional trends) under different fire regimes to provide biodiversity indicators of SFM.
- Simulations over landscape regions with medium pixel size (1–20 ha).
- Cover-type or stand-type succession models (Fire Behavior Prediction [FBP] fuel types).
- Inclusion of fire regime characteristics such as fire occurrence and fire size (as annual mean and variance).
- Fire growth models not necessarily needed.

Fire Effects Models

Most Canadian provinces, now realize that fire is an important component of the processes that occur in natural landscapes. Moreover, in the context of fire management, there is also an acknowledgment that fire will continue to occur. Therefore, to evaluate the short- and long-term frequency of fire, fire effects models are needed.

Model Characteristics

- Landscape to stand level (tactic to operational models).
- Time frame: years to century.
- Need to evaluate the short-term and long-term effects of fire on soils, vegetation, atmosphere (gas and smoke emission), and other aspects of the forest.
- Fire growth models with good estimates of behavior are required.
- Gaps: relationship between fire intensity and tree regeneration, tree mortality, and soil erosion; data on fuel consumption and gas emission under different fire behavior conditions.

Effects of Climate Change on Canadian Forests

Large-scale climate change may affect vegetation by altering the disturbance regime or by directly affecting the vegetation. However, the importance of natural disturbance processes in the boreal forest suggests that the effect of climate change on the disturbance regime may be more significant for forest dynamics than climatic change per se. In the context of global change, there is a need to assess the potential impact of the changing climate on Canadian forests through changes in the fire regime and the vegetation.

Model Characteristics

- Country-wide, strategic simulation model.
- Time frame: decade to century.
- Need to evaluate the direct effect of climate change on fire regime and vegetation, as well as the interactions between the two.
- Simulations over landscape regions with large pixel size (100–2500 ha).
- Broad vegetation types allowing succession models (FBP fuel types).
- Inclusion of fire regime characteristics such as fire occurrence and fire size (as annual mean and variance).
- Fire growth models not needed.
- Knowledge gap: relationships among weather, ignition, and area burned.

Fire Protection and Fire Management

Most fire protection agencies are currently experiencing a major change in their operational paradigm, evolving from a fire exclusion mandate to a fire management mandate. Therefore, they need new landscape fire models to assess fire danger and behavior over short periods, as well as models built into decision support systems to prioritize their actions during a crisis.

Model Characteristics

- Landscape level (tactic to operational models).
- Time frame: day to decades.
- Need to assess fire danger over short- and mid-term periods.
- Need to prioritize intervention sectors in crisis situations.
- Precise fire growth models are required.
- Gaps: real-time fire growth models linked to data on field features; weather data and interpolation tools; prediction of fire behavior for a variety of fuel types, not only the current FBP fuel types.

Conclusions

The degree of detail required by a landscape fire modeling effort is dictated by the objective of the study. The Fire Research Network can contribute to the development of different aspects of fire models with regard to the four areas discussed here.

References

Hunter, M.L., Jr. 1990. Wildlife, forests and forestry: principles of managing forests for biological diversity. Prentice-Hall, Engelwood Cliffs, NJ.

Hunter, M.L., Jr. 1993. Natural fire regimes as spatial models for managing boreal forests. Biol. Conserv. 65:115–120.

Fire-Impact Management

David L. Martell
Faculty of Forestry, University of Toronto
Toronto, Ontario, Canada M5S 3B3
E-mail: martell@smokey.forestry.utoronto.ca

Most forest and wildland fire management agencies were developed and grew on the assumption that fire is a destructive force. Their primary responsibility was, and largely remains, the development and implementation of fire exclusion strategies that minimize the area burned and thereby protect people and the things they value from fire damage. However, recognition that fire is a natural component of many forest ecosystems calls for new fire-impact management strategies under which decisions concerning wildfire suppression and the use of prescribed fire are based on the potential social, economic, and ecological impacts of fire.

Level-of-Protection Planning

Fire management agencies carry out level-of-protection planning to develop and evaluate strategies for balancing fire protection costs and fire damage. Most invoke or at least draw upon the basic least cost plus damage or LCD model, which stipulates that fire management expenditures should increase as long as each additional dollar spent reduces fire damage by at least one dollar. Recognition that fire can have beneficial impacts led to the development of the least cost plus net value change variant of the traditional LCD model. Many agencies strive to minimize area burned, subject to budget constraints, or they attempt to minimize the cost of achieving specified burned area targets. They often use computer simulation models and other computer-based decision support systems to predict how specified sets of fire suppression resources and policies will perform against specified fire loads.

Fire-Impact Management

One approach to resolving this complex problem is to begin by partitioning the fire management region into fire management analysis units (FMAUs) that are reasonably homogeneous with respect to land use and ecosystem processes and to identify the potential impact of fire on the things that people value in each FMAU. The next step is to specify a fire regime target (e.g., burn fraction), determine what resources will be allocated to each FMAU, and establish the policies and procedures that will govern their use and sharing to achieve those targets. The fire-impact management objective then becomes minimizing the cost of achieving those specified fire regimes.

Fire Impacts Ripple Across Landscapes and Over Time

FMAUs cannot be assessed in isolation from each other. Suppose we partition some large protected area, such as, for example, a province or a state, into a number of districts or forests. Because fire management needs vary across the landscape, it will be necessary to further partition the protected area into smaller FMAUs or compartments that are relatively homogeneous with respect to fire occurrence, behavior, and impact. Planners will tend to focus on and develop fire management plans for each FMAU, but it is important to note that the FMAUs will never be truly independent of one another. If, for example, there is a shortage of air tankers in one FMAU, its fires will have to wait for service in the initial attack queue. The longer fires wait, the larger they grow and the longer the time over which the air tankers will be required to service them. The congestion will grow, and subsequent fires will also have to wait longer for service. Busy air tankers cannot be loaned to other FMAUs and their fires will be affected by shortages in other FMAUs on previous days. Fire managers will need to develop hierarchical, iterative planning procedures for fire-impact management that will deal, for example, with initial burn-fraction targets and procedures for achieving them in each FMAU, and then allow these targets to move to a higher level in the hierarchy where the managers can reconcile conflicting demands for fire management resources that the agency owns or can borrow from other agencies.

Some Issues and Concerns

Explicit recognition that fire and the uncertainty it brings are natural poses significant challenges to fire management agencies and the stakeholders they are designed to serve.

Learning to Cope with Uncertainty

Forests and the flows of timber and other resources exploited by people are shaped by complex stochastic processes that cannot be rigidly controlled. We need to accept less stability in the flows of economic returns. The lack of stability is caused by the variability that produces the biodiversity we enjoy and which is essential to maintain natural ecosystem processes. One can, for example, use stochastic timber supply models to explore the extent to which we can trade off economic returns, harvest levels, and harvest flow stability, and reconcile those measures with the extent to which we interfere with the integrity of natural ecosystem processes.

Estimating the Parameters of the Fire Regime

A forest landscape is a realization (essentially one very large observation or data point) of many complex stochastic processes that vary over both time and space. We are limited to taking "snapshots" of such landscapes at a very few points in time and then using those sparse observations to estimate ecosystem parameters (e.g., the fire cycle) with very broad confidence intervals.

Managing Ecosystem Processes, Not Forest Age Classes

The time between fires at a single point has a probability distribution, and the age-class distribution of forest stands also has a probability distribution. Natural and human processes will produce specific realizations of the age-class distribution of a forest that will almost always differ from the theoretical distribution; the extent to which that is the case is partly a scale issue. It is important to note that what appear to be discrepancies in age-class distribution do not necessarily call for corrections. We should attempt to manage fire cycles, not the age-class distributions they produce. In very simple terms, we should not attempt to "mow" the forest to the theoretical age-class distribution through harvesting or fire or some combination of these.

Applications in Forest and Vegetation Management—Alberta's Perspective

Cordy Tymstra
Fire Management Planning, Forest Protection Division, Alberta Land and Forest Service
10th Floor, 9920 – 108 Street, Edmonton, Alberta, Canada T5K 2M4
E-mail: Cordy.Tymstra@gov.ab.ca

Forest management planning has traditionally been based on the principle of sustained yield management. Although this is the legislative requirement under the *Forests Act*, the Government of Alberta has endorsed the concept of sustainable forest management (Alberta Department of Environmental Protection 1998). Forest companies are encouraged to adopt this new approach to forest management planning.

Several provincial government documents—*Alberta's Commitment to Sustainable Resource and Environmental Management* (Government of Alberta 1999), *The Alberta Forest Legacy: Implementation Framework for Sustainable Forest Management* (Alberta Department of Environmental Protection 1998), and the *Interim Forest Management Planning Manual—Guidelines to Plan Development* (Alberta Land and Forest Service 1999)—provide direction for implementing of sustainable forest management. Although strategic directions have been identified, the challenge remains in setting operational goals and monitoring. As Bunnell and Johnson (1998) eloquently stated, "Policy makers, researchers and practitioners must choreograph the dance of values to the living dance of the forest." In Alberta, the "dance of values" will be choreographed by defining a future desired forest and by setting landscape-level objectives (regional and subregional objectives and strategies). The regional and subregional objectives provide direction for the operational plans (e.g., detailed plans for forest management, water resources, and special places). This planning process is being developed under a new integrated resource management planning framework.

The National Forest Strategy (CCFM 1998) identifies nine strategic directions. The second strategic direction, "Forest Management: Practicing Stewardship," recognizes that fire is a natural process and that, in some fire-dependent forests, periodic fires are essential to maintain forest health. There is also recognition that fire-suppression activities can alter the characteristics of the forest. The National Forest Strategy suggests that "There is a challenge to find a level of fire suppression that balances short-term and long-term needs." The second strategic direction also suggests that silviculture and harvesting can be changed to result in more natural conditions, which would inherently reduce the risk of losses from fire.

Forest management planning should therefore include consideration of fire, recognizing both the ecological role of fire (positive effects) (Wright and Heinselman 1973; Weber and Stocks 1998), and the potential threat of wildfire to the resources being managed (negative effects) (Richardson 1971; Gould and Hutchings 1995).

Alberta is developing an approach to the integration of fire management and forest management based primarily on the use of spatial assessments of wildfire threat on the landscape. Assessment of wildfire threat includes assessments of fire behavior potential, fire risk, values at risk, and suppression capability (Hawkes and Beck 1997). The overall approach for integrating fire management and forest management involves the following steps:

1) Spatial assessment of potential fire behavior (i.e., fuels, weather, topography, and system outputs for Fire Behavior Prediction [FBP]).

2) Spatial assessment of fire risk (i.e., lightning and actual fire starts).

3) Spatial assessment of fire regime characteristics.

4) Spatial assessment of suppression capability.

5) Spatial assessment of the values at risk.

6) Identification of barriers to fire spread.

7) Assessment of the forest-level impact of fire (i.e., uncertainty of fire and critical age classes).

8) Integration of landscape-level fire management strategies with other landscape objectives and strategies.

A number of tools and models are used in Alberta to assist in assessing wildfire threat. The AVI2FBP program is a standalone C program that assigns one of the 16 Canadian Forest Fire Danger Rating System FBP fuel types to each Alberta Vegetation Inventory (AVI) polygon. Each fuel type is distinct and potentially yields different fire behavior characteristics. FBP fuel type maps provide a good initial assessment of fire behavior potential at a broad scale. This is useful for identifying landscape-level fire management strategies.

The CROSUM program is an ArcView™ application that also evaluates AVI stand attributes. This program assigns a relative susceptibility to crowning class to each AVI polygon. The CROSUM program provides an additional layer of information and helps to further stratify the landscape, in particular those areas classified as C-2 (Boreal Spruce) and C-3 (Mature Jack or Lodgepole Pine), with respect to crowning potential. The CROSUM model provides a spatial assessment of the probability of large fire runs. This information is useful for sequencing stands and compartments and for strategically establishing barriers to the spread of fire.

The Spatial Fire Management System (SFMS), developed by the Canadian Forest Service in collaboration with fire management agencies, is a decision support system used in forest fire preparedness planning. SFMS produces spatial grids of the FBP system outputs, such as head fire intensity. Historical weather data can also be used to build percentile maps (Kafka et al. forthcoming), which are useful for identifying areas that consistently have the highest wildfire threat.

The AVI2FBP, CROSUM, and SFMS applications can be used to assess wildfire threat across the entire landscape. The AVI2FBP and CROSUM models are licensed programs that the Forest Protection Division of Alberta Land and Forest Service distributes free to industry (forest companies and forest consulting companies) and government. The objective is to ensure that standard tools, and hence consistent outputs, are used by all stakeholders. Alberta is also participating on an integrated, interdisciplinary team to develop the Canadian Wildland Fire Growth Model. This model can be used in a planning mode (i.e., deterministic model runs) to evaluate the threat of wildfire to key values at risk. The effectiveness of alternative forest management strategies (e.g., harvest scheduling, cutblock layout and design, or silviculture) to mitigate the threat of wildfire (in essence, to "cool the forest"), in particular, large, high-intensity fires, can also be assessed with this model.

The Canadian Wildland Fire Growth Model can be run repetitively to evaluate the burn probability of current and future forests. In this manner, multiple runs can be completed to spatially assess burn probability across the landscape. Incorporating succession models for vegetation or linking the fire growth model to landscape disturbance models will enhance our understanding of the role of fire in establishing and maintaining landscape patterns.

In Alberta, fire is the dominant disturbance agent on the landscape. Although Alberta has developed expertise and capability to suppress fire, major wind-driven fire events continue to challenge fire-control efforts. Various strategies and tactics will be applied to mitigate the effects of these events on the landscape and to protect fire-adverse communities and other values at risk. Mitigating wildfire threat must, however, be accomplished while recognizing the ecological role of fire in fire-dependent forest ecosystems. This requires an understanding of the "living dance of the forest". In Alberta, future forests will be designed and managed to address both these needs.

References

Alberta Department of Environmental Protection. 1998. The Alberta forest legacy: implementation framework for sustainable forest management. Alta. Environ. Prot., Edmonton, AB. Publ. 1-689.

Alberta Land and Forest Service. 1999. Interim forest management planning manual: guidelines to plan development [on-line]. Alta. Environ. Prot., Alta. Land For. Serv., Edmonton, AB. <http://www.gov.ab.ca/env/forests/fmd/manuals/index.html>

Bunnell, F.L.; Johnson, J.F. 1998. Policy and practices for biodiversity in managed forests, the living dance. UBC Press, Vancouver, BC.

(CCFM) Canadian Council of Forest Ministers. 1998. National forest strategy 1998–2003. Sustainable forests: a Canadian commitment. Can. Counc. For. Minist., Ottawa, ON.

Gould, J.S.; Hutchings, P.T. 1995. The January 1994 fires in NSW, Australia: bushland/urban issues. Pages 103–106 *in* C. Tymstra, comp. Fire management in the wildland/urban

interface: sharing solutions. Proc. Symp., October 2–5, 1994, Kananaskis Village, AB. Partners in Protection, Edmonton, AB.

Government of Alberta. 1999. Alberta's commitment to sustainable resource and environmental management. Gov. Alta., Edmonton, AB.

Hawkes, B.; Beck, J. 1997. A wildfire threat rating system. Nat. Resour. Can., Can. For. Serv., Pac. For. Cent., Victoria, BC. Tech. Transfer Note 1.

Kafka, V.; Tymstra, C.; Hirsch, K.; Flannigan, M. n.d. Assessing fire behaviour potential: a comparative analysis of two techniques. *In* Crossing the millennium: integrating spatial technologies and ecological principles for a new age in fire management. Proc. Joint Fire Sci. Conf. Workshop, June 15–17, 1999, Boise, ID. Forthcoming.

Richardson, J.H. 1971. Values protected in Alaska. Pages 173–178 *in* C.W. Slaughter, R.J. Barney, and G.M. Hansen, eds. Proc. Symp. Fire North. Environ., April 13–14, 1971, Fairbanks, AK. U.S. Dep. Agric., For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, OR.

Weber, M.G.; Stocks, B.J. 1998. Forest fires and sustainability in the boreal forests of Canada. Ambio 27(7):545–550.

Wright, H.E.; Heinselman, M.L. 1973. The ecological role of fire in natural conifer forests of western and northern North America. Quat. Res. 3:317–328.

Description and Uses of FARSITE

Mark A. Finney
USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory
P.O. Box 8089, Missoula, Montana, USA 59807
E-mail: mfinney@fs.fed.us

FARSITE (fire area simulator) is a mechanistic fire growth simulation model (Finney and Andrews 1999). It simulates the expansion of elliptical fire fronts across complex landscapes where fuels, weather, and topography are variable (Finney 1998). It includes submodels for surface fire, crown fire, fire acceleration, fuel moisture, and spotting from torching trees. It was originally developed for long-range projection of active fires in national parks and wilderness areas in the USA (Finney 1994; Finney and Ryan 1995). These areas had made early investments in the data on spatial fuels and vegetation required to run such a model (see Keane et al. 1998a). Until recently, however, there were no data for the vast majority of lands in the USA, and this technology could not be used. The increased availability and capability of geographic information systems (GIS) (Finney 1995) has made possible the processing and development of spatial data for large areas of the western USA.

The greater availability of spatial GIS data on fuels and vegetation has led to the increasing use of FARSITE for decision support for short-range projections on active wildland fires and for fire planning (Van Wagtendonk 1996; Finney et al. forthcoming). FARSITE runs on a personal computer under the Microsoft Windows® operating system but requires the use and support of a GIS to provide spatial data. Other uses for FARSITE have been to simulate ecological patterns of fire effects (Keane et al. 1997, 1998b) and to explore the spatial implications of fuel treatments (Finney forthcoming). The mechanistic approach to producing fire behavior and effects facilitates the simulation of complex patterns of fire behavior and effects, as well as the investigation into their causes, in terms of dependence on various combinations of fuels, weather, topography, and relative spread direction (Finney 1999).

Not all fire behaviors and spatial or temporal patterns can be simulated, however. The resolution of the input data limits the absolute level of detail in simulations of fire behavior and effects. Indeed, many important fire behaviors and effects will always require data at finer scales than are possible for landscape-level simulations (e.g., spot fire ignition). In these cases, stochastic approaches must be substituted. The fire behavior models that constitute FARSITE are themselves limiting in the range of conditions to which they apply and the kinds of behaviors modeled. By recognizing and illustrating these limitations, research into fire behavior can be focused and improvements compared with previous performance.

New behaviors and improvements are envisioned for the next year. These are primarily concerned with simulating spatial and temporal patterns of postfrontal combustion. Many modifications of FARSITE have been made to enable modeling of fire activity (Albini and Reinhardt 1995) behind the fire front. These will lead to estimates of smoke production, which is perhaps one of the most critical limitations on the use of fire in the western USA. A new dead-fuel moisture model will also be incorporated to improve sensitivity of fire behavior to diurnal weather changes and to topographic influences.

References

Albini, F.A.; Reinhardt, E.D. 1995. Modeling the ignition and burning rate of large woody natural fuels. Int. J. Wildland Fire 5(2):81–92.

Finney, M.A. 1994. Modeling the spread and behavior of prescribed natural fires. Pages 136–143 *in* Proc. 12th Int. Conf. Fire For. Meteorol., October 26–28, 1993, Jekyll Island, GA. Soc. Am. For., Bethesda, MD.

Finney, M.A. 1995. FARSITE: a fire area simulator for fire managers. Pages 55–56 *in* D.R. Weise and R.E. Martin, tech. coords. The Biswell Symposium: fire issues and solutions in wildland ecosystems, February 15–17, 1994, Walnut Creek, CA. U.S. Dep. Agric., For. Serv., Pac. Southwest Res. Stn., Berkeley, CA. Gen. Tech. Rep. 158.

Finney, M.A. 1998. FARSITE: fire area simulator—model development and evaluation. U.S. Dep. Agric., For. Serv., Rocky Mt. Res. Stn., Missoula, MT. Res. Pap. RMRS-RP-4.

Finney, M.A. 1999. Mechanistic modeling of landscape fire patterns. *In* D.J. Mladenoff and W.L. Baker, eds. Spatial modeling of forest landscapes: approaches and applications. Cambridge Univ. Press, New York, NY.

Finney, M.A. n.d. Spatial patterns of fuel treatments and some effects on fire growth and behavior. *In* Crossing the millennium: integrating spatial technologies and ecological principles for a new age in fire management. Proc. Joint Fire Sci. Conf., June 15–17, 1999, Boise, ID. Forthcoming.

Finney, M.A.; Andrews, P.L. 1999. FARSITE: Fire area simulator—a model for fire growth simulation. Fire Manage. Notes 59(2):13–15.

Finney, M.A.; Ryan, K.C. 1995. Use of the FARSITE fire growth model for fire prediction in US National Parks. Pages 183–189 *in* Proc. Int. Emergency Manage. Eng. Conf., May 1995, Sofia Antipolis, France.

Finney, M.A.; Sapsis, D.B.; Bahro, B. n.d. Use of FARSITE for simulating fire suppression and analyzing fuel treatment economics. *In* Symposium on fire and California ecosystems: integrating ecology prevention and management, November 1997. Forthcoming.

Keane, R.E.; Garner, J.L.; Schmidt, K.M.; Long, D.G.; Menakis, J.P.; Finney, M.A. 1998a. Development of the input spatial data layers for the Selway–Bitterroot Wilderness Complex, USA. U.S. Dep. Agric., For. Serv., Rocky Mt. Res. Stn., Missoula, MT. Gen. Tech. Rep. 3.

Keane, R.E.; Ryan, K.C.; Finney, M.A. 1998b. Simulating the consequences of fire and climate regimes on a complex landscape in Glacier National Park, Montana. Pages 310–324 *in* T.L. Proden and L.A Brennan, eds. Fire in ecosystem management: shifting the paradigm from suppression to prescription. Proc. 20th Tall Timbers Fire Ecol. Conf. Tall Timbers Res. Stn., Tallahassee, FL.

Keane, R.E.; Hardy, C.C.; Ryan, K.C.; Finney, M.A. 1997. Simulating effects of fire on gaseous and atmospheric carbon fluxes from coniferous forest landscapes. World Resour. Rev. 9(2):177–203.

Van Wagtendonk, J.W. 1996. Use of a deterministic fire growth model to test fuel treatments. Pages 1155–1165 *in* Sierra Nevada Ecosystem Project: final report to Congress, vol. 2. Assessments and scientific basis for management options. Univ. Calif., Cent. Water Wildland Resour., Davis, CA.

Exploring Possibilities in Nature using LANDMINE

David W. Andison
Bandaloop Landscape Ecosystem Services
30 Debra Ann Road, Golden, Colorado, USA 80403
E-mail: Andison@AOL.com

Like many others at this workshop, I developed a computer simulation model that spreads disturbances across a landscape. Sharing some of the differences and similarities between different models is part of the reason we are here. However, before I go over some of the specifics of LANDMINE, I want to provide some background.

The study of disturbances, natural and otherwise, has become very popular over the past decade. This is due, at least in part, to the recognition that disturbance, as a process, introduces much of the stochasticity we see in landscapes today. In other words, the study of disturbance tells us a lot about how and why landscapes are dynamic in both time and space. The historical dynamic nature of landscapes has been referred to as the "natural range of variability."

Studying, quantifying, and somehow emulating the natural range of variability is quickly becoming the dominant forest management strategy in North America. This strategy is predicated on the assumption that by following nature's lead, we will be saving most of the biological pieces that we value, as well as those we do not know about yet. In other words, it is one strategy of working toward ecological sustainability. Whether or not you buy in to this argument, using historical precedent as a management template is attractive from a practical point of view. Unlike many of the alternative strategies, "pattern" is quantifiable. This means it can be translated easily into planning goals and monitoring targets. Perhaps of greater significance is the fact that the natural range of variability potentially creates a solution space for management planning that is quite broad. This allows for other planning constraints and values to fit within the natural-pattern strategy framework rather than being in conflict with it.

Given the task of studying disturbance, researchers in this field quickly discovered that the time and space scales involved required some innovative techniques—thus, many of us turned to modeling. In my case, I wanted something that could be run on a personal computer, that could be used or called by other programs (therefore, LANDMINE is written in C++), and that could use whatever spatial data were available. It also had to capture and accurately portray the most important patterns of fire behavior over large areas: frequencies, sizes, shapes, and unburnt areas. It should be kept in mind that this is not a fire behavior model, but rather a landscape disturbance model.

The guts of the LANDMINE model grows disturbances as "firelets." The directional movement of the firelets is stochastic, based on the probabilities of fire movement in one of eight directions from a source pixel. The scores for each pixel are built using several layers, including fuel type (converted from inventory types to the Fire Behavior Prediction types), slopes and aspects, and any other burning tendencies such as creeks. For instance, I can lower the probability of a fire crossing a creek by simply assigning a multiplication factor of 0.50 to each creek pixel. I can also use multiplication factors to incorporate research I have been doing lately on where islands tend (and tend not) to form (based on land position information).

The firelet idea is an elegant one (for which I cannot claim credit), and it allows patterns to be manipulated. For instance, by changing the length of the firelet, the probability of it spawning a new firelet, and the probability of a firelet being extinguished, the shape of the disturbance and the area and number of unburnt islands can be controlled. With the appropriate research, the model can thus be calibrated to specific landscapes. I can also mimic regularly shaped cut blocks with no islands by manipulating the same three factors.

The firelet concept is also handy because I can simply stop the fire growth when it has reached the predetermined disturbance size. Fire sizes are chosen stochastically from an equation derived

from the raw landscape data. Fire sizes are chosen until the total area to be disturbed for a time step is complete. At the highest level of the model, a disturbance frequency equation is used to stochastically select the amount of disturbance in each time step. This equation is also defined from raw landscape data.

As my research continues, the calibration exercise becomes more involved. It now involves burn shapes, numbers and sizes of island remnants, probability of disturbance of riparian areas, and probability of subsequent burns (within a given time step).

One of the advantages of a pixel-based model is that it can be used at several different scales. The following three examples demonstrate how I have used LANDMINE at different scales. The first is from a project I did for Weldwood in Hinton, Alberta. The company was concerned about defining a single target for old-growth retention in their long-term plan and was intrigued by the idea of a moving target. Using a 4-ha pixel, I ran LANDMINE 100 times to get a sense of the temporal pattern of the seral stages based on historical data. Because Weldwood was not interested in the spatial arrangement at this point, I summarized the model output aspatially.

Weldwood learned two important things from the exercise. First, in most cases, the current and projected percentage of each age class was well within the simulated historical range. The single exception was the extremely high amount of "old-growth" forest in the boreal mixed-wood area. This area had for the past 40 years been well protected from fire and had not been extensively logged. Second, the "old-growth" forest was dynamic in space, and the modeling exercise indicated that, at a certain scale, it should not be maintained in all places on the landscape. Both lessons were incorporated into Weldwood's recent long-term management plan to actively move and cluster old patches of forest.

The second example of the use of LANDMINE was in northern British Columbia. As part of the pilot study for the new landscape guidelines of the B.C. Biodiversity Guidelines, the provincial Ministry of Forests asked for 10 landscape plans from across the province. In Prince George, the group responsible for one such plan asked me to use LANDMINE to compare the long-term impacts of the biodiversity guidelines and of the existing three-pass system with the "natural" pattern. In this case I used 1-ha pixels and more involved calibration. The results of 50 runs forward in time for each scenario were fed through FRAGSTATS and compared. Overall, the results showed that the new "ecologically sensitive" rules, including a 1000-ha upper limit on harvest blocks, did little or nothing to create more "natural" patterns. The main problems were green-up requirements, riparian buffers holding most or all of the "old growth," and the inadequacy of the 1000-ha upper size limit. The projected landscapes resulting from the guidelines were almost as fragmented as those resulting from the 60-ha, three-pass harvesting system.

At the finest level of resolution, I have used LANDMINE to demonstrate harvest-event design considerations in both Alberta and Saskatchewan. At 0.25-ha resolution, the eligibility requirements of landscape elements can be manipulated to create spatial constraints. For instance, in this exercise I did not allow any riparian pixels to be disturbed, which limited the disturbance to the area within the bounds of these corridors on the landscape. This single constraint created disturbances with very different configurations from those of "natural" runs. By allowing limited relaxation of the constraint—in this case, two predetermined river "crossings"—the disturbance configuration came close to the "natural" runs.

I often use the last of these examples to demonstrate the power of simulation modeling as a planning tool but also the flexibility of a natural pattern strategy. As with the other two examples, using knowledge of natural patterns opens up possibilities, as opposed to imposing more rules. Furthermore, the visual impacts of examples such as these are powerful tools for understanding.

The level of acceptance and use of the natural-pattern strategy varies widely, even in western Canada. Generally speaking, I am still educating my clients, and I expect to be doing so for some time. As easy as the concept of change and natural variation may be to some of the participants in this workshop, they are radically different ideas for the forest planner. And as useful as LANDMINE has been to me as a scientist, its greatest value to me as a consultant has been in allowing me to introduce the concept of change and disturbance as a process. In most cases, clients soon begin to see for themselves how useful the idea can be in a practical sense.

Spatial Fire Regime Simulation in a Spatially Explicit Model for Landscape Dynamics (SEM-LAND)

Chao Li
Northern Forestry Centre, Canadian Forest Service
5320 – 122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: cli@nrcan.gc.ca

Abstract

Spatial fire regime simulation is one of the major components of the SEM-LAND model. The fire simulation in SEM-LAND attempts to give forest resource managers a means for assessing the impact of fire on landscape dynamics. The objective of this study was to develop a model that could simulate the interactions among forest fire events, landscape structure, and climatic conditions under various scenarios, including climate change. A conceptual model of fire processes will be presented, and its implementation in the fire regime simulation will be described, including the calculation of fire probability and the effects of fuel type, slope, and weather conditions. The model requires data on the structure of the landscape under investigation, pattern of fire ignition source, and weather conditions. The model output includes both spatial maps and nonspatial summaries. The model was validated by observations from a study area in west-central Alberta, as well as other qualitative criteria such as fire size distribution, irregular fire shapes, and remnants within the simulated burned areas. A number of model applications will also be briefly presented.

TELSA: the Tool for Exploratory Landscape Scenario Analyses

Werner A. Kurz
ESSA Technologies Ltd.
1765 West 8th Avenue, Vancouver, British Columbia, Canada V6J 5C6
E-mail: wkurz@essa.com

Sarah J. Beukema
ESSA Technologies Ltd.
1765 West 8th Avenue, Vancouver, British Columbia, Canada V6J 5C6
E-mail: sbeukema@essa.com

Walt Klenner
B.C. Ministry of Forests
515 Columbia Street, Kamloops, British Columbia, Canada V2C 2T7
E-mail: Walt.Klenner@gems7.gov.bc.ca

Spatial characteristics of landscapes, such as fragmentation, patch-size distribution, and connectivity, are largely determined by the interaction of vegetation dynamics, natural disturbances, and management activities. Managers of forest ecosystems require tools with which they can assess and communicate the impacts of alternative management choices on the range and variability of future landscape characteristics. Such tools should permit the stakeholders in the planning process to determine and consider the trade-offs among the available management options using a wide range of spatial and nonspatial indicators. Moreover, the projection tools should make all assumptions and functional relationships easily accessible, to ensure that all parties involved in the planning process clearly understand the results of scenario analyses.

TELSA is a spatially explicit model of vegetation succession, natural disturbances, and forest management activities (Kurz et al. forthcoming). It is a strategic planning tool designed to support adaptive management by projecting the consequences of alternative scenarios at the scale of landscape units (i.e., 10 000 to 250 000 ha) over time frames of decades to centuries. TELSA represents forest succession and the impacts of management and natural disturbances as changes in species composition, age, and structural stages of stands. Successional pathway diagrams developed with the Vegetation Dynamics Development Tool (Beukema and Kurz 1998) define the transition times between various succession classes (defined by species composition and stand development stage or age) and the probabilities and impacts of disturbance by insects, fire, or other agents. These diagrams also define the impacts of forest management actions on stand structure and composition. TELSA's approach to succession modeling is simple but effective, and minimizes the need for detailed inventory information for each polygon in the landscape. Such information is typically not available for parks and other areas that are not managed for timber.

TELSA is a modeling framework that allows users to define successional pathway diagrams specific to the ecological and biophysical conditions of the landscape in question. Users also define the silvicultural systems and the rules for forest management activities that the model schedules on the basis of current conditions of the landscape. For example, these rules can specify the conditions under which salvage logging can follow natural disturbance events, such as fire or insects. This approach ensures continuous feedback between landscape conditions, natural disturbances, and management actions.

The TELSA model comprises the main simulation model and several other programs that assist the user in preparing spatial and other input data, in defining various management scenarios, and in analyzing, comparing, and displaying the simulation results. TELSA combines commercial software products (such as the Access™ database, and ArcView/Spatial Analyst™) with a simulation model and interfaces to the database and geographic information systems. TELSA runs on high-end

personal computer platforms with Windows 95® or Windows NT® operating systems. The TELSA toolbox includes a tool for the automated design of management units (e.g., harvest cut blocks), based on user-defined criteria and scenario objectives. TELSA easily evaluates strategic alternatives regarding the size range of management units, their spatial aggregation, the use of adjacency constraints, and the application of different silvicultural and harvesting systems such as partial cutting, patch cutting, clear-cutting, or aggregated harvest areas.

Natural disturbances are simulated according to the probability of disturbances of each successional class, the amount of each successional class in the landscape, user-defined between-year variability for each disturbance type, and any external trends such as climate change or protection efforts (Kurz et al. forthcoming). In addition, information about the size-class distribution of disturbances is required by the model. Using multiple Monte Carlo simulations of natural disturbance scenarios, users can assess the range and variability of landscape indicators and the distribution of disturbances in space and time.

TELSA results can be viewed as maps, graphs, or tables, for the entire landscape or for strata within the landscape, through user-friendly interfaces. Because all results are stored in an Access database, users can compare results of different scenarios or multiple Monte Carlo runs of one or more scenarios. Basic information such as area disturbed (including the range of area disturbed or the probability of disturbance for different polygons), age-class distribution, and seral-stage distribution can be graphed and mapped. Additional spatial indicators, such as count and area distribution of patch-size classes and old-growth interior habitat and the length of edge between different seral stages or age classes, are also calculated. Because the state of every polygon is known for every reporting time step, further postprocessing for wildlife habitat interpretation or other analyses is possible.

TELSA was developed to support strategic planning in British Columbia and has been applied to case studies in the southern interior of the province (Klenner et al. forthcoming), in northwestern British Columbia, in northern Alberta, and in western USA. It can be applied readily to other regions and ecosystem types where users can provide parameters on vegetation dynamics, natural disturbances, and the impacts of management actions.

Acknowledgments

TELSA was developed with funding from Forest Renewal B.C. and ESSA Technologies Ltd.

References

Beukema, S.J.; Kurz, W.A. 1998. Vegetation Dynamics Development Tool user's guide, version 3.0. ESSA Tech. Ltd., Vancouver, BC. (Available for download <http://www.essa.com/forestry/VDDT>.)

Klenner, W.; Kurz, W.A.; Beukema, S.J. 2000. Habitat patterns in forested landscapes: management practices and the uncertainty associated with natural disturbances. Comput. Electron. Agric. 27(1–3):243–262.

Kurz, W.A.; Beukema, S.J.; Klenner, W.; Greenough, J.A.; Robinson, D.C.E.; Sharpe, A.D.; Webb, T.M. 2000. TELSA: the tool for exploratory landscape scenario analyses. Comput. Electron. Agric. 27(1–3).227–242.

Multiscale Models of Fire in Boreal Forests

Steve Cumming
Boreal Ecosystems Research Ltd.
6915 – 106 Street, Edmonton, Alberta, Canada T6H 2W1
E-mail: stevec@berl.ab.ca

In this talk, I outlined the empirical foundations for some fire models. These models are components of a more far-reaching initiative: developing an integrated suite of simulation models of landscape dynamics in the boreal mixed wood. At present, these models incorporate the dynamics of white spruce and aspen, the abundance and distribution of numerous forest bird species, the design of protected areas, and detailed behavioral models of the forest industry, as well as wildfire. Many of these processes interact. Forest management can be viewed as proceeding at the tactical level, where decisions about cut-block scheduling are made, and at the strategic level, where the patterns of harvesting over large spatial and temporal scales are determined. My colleagues and I are therefore developing a closely linked pair of modeling tools, each of which deals with ecological and management processes at a different scale. Feenix is the tactical model, operating at a resolution of less than 10 ha and an extent of up to 300 000 ha. Tardis is the strategic model, with a resolution of 10 000 ha, and an extent of 10 000 000 ha. Both models derive a representation of the forest from forest inventory data. Feenix uses gridded digital inventory maps and classifies the forest for fire-modeling purposes into six or seven classes based on dominant tree species. Tardis uses spatially aggregated stand lists, which are classified on the fly into the requisite categories, as needed. Here, I describe how fire is modeled in these two frameworks and how parameters are estimated from a common database. In Feenix, individual fires are modeled by a percolation or cellular automata process, whereby a fire spreads from cell to cell probabilistically. In Tardis, the approach is purely statistical. The parameter estimation process, fascinating in itself, has yielded some interesting theoretical insights as a by-product.

I regard fire as a three-stage stochastic process: ignition, initial spread, and extinction. The ignition stage is common to both scales. Detected ignitions (fires that become large enough to be detected by a comprehensive network of fire towers) are modeled as an inhomogeneous Poisson process. The raw data are counts of detected fires over a 26-year interval. Ignitions are spatially registered to within 10 000 ha rectangles. Forest inventory data generated spatial covariates which, by general linear models, explain more than 50% of the deviance in the count data. In Tardis, for each grid cell and each 5-year time step, the number of ignitions is sampled from a Poisson distribution with the mean predicted by the model. This mean changes with forest harvesting and succession. In Feenix, which runs at an annual time step, the expectation per model cell is very low, and ignition density can be approximated by drawing from a uniform (0,1) distribution.

The second stage, initial spread, is also common to both scales, although the implementation details are different. Given that a fire has started, we estimate the conditional probability that it will reach some threshold size (say 9 ha). This probability incorporates several factors, including fire-suppression effort. The probability is estimated directly from the final size associated with each recorded fire. This probability varies with the time course of fire-suppression effort and strategy, and thus shows that fire suppression is effective. In Tardis, simulated ignitions are allowed to pass the threshold if a uniform (0,1) random number exceeds a critical value (about 0.95). In Feenix, the spread probabilities are specially computed for new fires, so as to achieve the desired conditional probability.

The desired conditional probability is achieved by tuning the spread parameters so that the size distribution of fires larger than 9 ha is as close as possible to the observed distribution. Empirical and simulated size distributions were compared by Anderson Darling tests and yielded an estimate of 0.24, well below the percolation threshold. Rare, large fires (exceeding 100 000 ha) occur nonetheless. The interannual variability in simulated area

burned approximates the empirical values. It is therefore not necessary to model interannual variability in fire weather by drawing the spread parameter from some distribution. Neither is it necessary to vary the spread parameter during the time course of a fire, as is done for some detailed individual-fire behavior models. In Tardis, fire growth and extinction are modeled by drawing a final size(s) from a parametric model. For fires exceeding 9 ha, log(s) follows a truncated exponential distribution. The maximum fire size is estimated to be about 1 million ha for my study area, which is essentially the northeast corner of Alberta. The advantage of a parametric model is that the affect of covariates on fire size can be explored. For instance, at Tardis resolution, the abundances of pine forest and recently disturbed areas have, respectively, positive and negative effects on expected fire size. In Tardis, it is necessary to determine which stands actually burn in a given fire. This is done using a multivariate linear regression model that relates the composition of a fire to the composition of the area in which it burned. The model was estimated from a sample of 48 mapped fires, with a multivariate r^2 of 0.62. Having determined the size of a fire, a bounding box enscribing a circular fire of that size is determined, and the fire composition is then predicted using the statistical model. A set of heuristic rules are then used to find an appropriate set of stands to mark as burned. In Feenix, fire compositions emerge from the growth process. There is potential to estimate class-specific spread parameters by applying simulated likelihood methods to the statistical model of fire compositions, but this step has not been taken.

The statistical model has yielded two ancillary results. One bears on the controversy regarding the importance of fire weather. Fires are highly selective with respect to stand types burned across many spatial scales, and across all size classes. It follows that fuels influence fire behavior even under extreme conditions. It can also be shown from the model that certain forest management practices reduce the hazard associated with burning valuable white spruce stands. In other words, not only is "cooling the forest" possible, but the practice can be evaluated quantitatively.

A final complexity is that of spatial variability in fire intensity, as reflected in resultant patterns of burn severity. My colleagues and I are assembling archival data sets, which we expect will yield statistical models of this variability.

LAMOS: a LAndscape MOdelling Shell

Sandra Lavorel
Centre d'écologie fonctionnelle et évolutive, Centre national de la recherche scientifique
UPR 9056, 1919, route de Mende, 34293 Montpellier, Cedex 05, France
and
Ecosystem Dynamics Group, Research School of Biological Sciences
Institute of Advanced Sciences, Australian National University
Canberra, ACT 0200, Australia
E-mail: lavorel@cefe.cnrs-mop.fr

Ian D. Davies
Ecosystem Dynamics Group, Research School of Biological Sciences
Institute of Advanced Sciences, Australian National University
Canberra, ACT 0200, Australia
E-mail: ian.davies@anu.edu.au

Ian R. Noble
Ecosystem Dynamics Group, Research School of Biological Sciences
Institute of Advanced Sciences, Australian National University
Canberra, ACT 0200, Australia
E-mail: noble@rsbs.anu.edu.au

Context and Purpose

Recent work has shown that the behavior of landscapes with spatially linked processes such as dispersal and lateral flow of resources is quite different from the behavior of the same plants and animals represented as point models (e.g., Noble and Gitay 1996; Rupp et al. forthcoming). Feedback, such as that between disturbance regimes and community composition, can lead to persistent, self-generated patterns that in turn change the overall composition and dynamics of the landscape communities. Many of these interactions can be explored only be modeling. The past 10 years have seen a proliferation of landscape simulation models, facilitated by the ever-increasing availability of computing power. However, this activity has been mainly uncoordinated, as it has developed in the absence of a general landscape theory or at least of well-recognized benchmarks. This has in particular been the case for landscape fire models (Gardner et al. 1999).

LAMOS is a landscape modeling environment designed to allow users to explore the role of different processes in the dynamics of landscapes with a minimum of programming effort. LAMOS was specifically designed for the following tasks:

- to carry out formal comparisons of existing models, examining sensitivity to processes, to modeling methods, and to parameterization;
- to assemble new models from an existing toolbox by mixing and matching available methods for each process; and
- to create new models by assembling precoded methods for some processes with new methods for specific modules; for example fire modelers may wish to include specific methods for fire propagation without having to reinvent a method for succession modeling.

Model Description

General Shell Design

LAMOS factors landscape dynamics into four principle processes with a clearly defined set of interactions. These processes, their interactions, and global environmental information define the shell and its basic assumptions. These processes are succession, which operates at the patch scale; and disturbance, dispersal, and lateral flow of materials, all three of which operate at the landscape scale.

The aim of this design is to allow various approaches to modeling these processes to be

incorporated within the shell without breaking any fundamental assumptions that may underlie the program. In particular, the structure makes it possible to link processes that are modeled at differing temporal resolutions for each process. Much of the challenge in designing LAMOS has been in establishing a flexible structure that allows for complete modularity, while ensuring standardized communication across modules.

Biological Units: Plant Functional Groups

Vegetation is described by its functional group (FG) composition. FGs are user-defined groups of taxa with similar behavior (Gitay and Noble 1997). They share biological attributes that determine their response to environmental conditions, their competitive ability, their response to disturbance, their reproduction and dispersal, and their regeneration strategies. For any given model, a set of FGs is predetermined, and these are the biological units through which succession, dispersal, disturbance dynamics, and resource flows are modeled. LAMOS can have any number of functional groups within the shell (although the data generated from large numbers of FGs can be difficult to analyze).

Succession

The succession module deals with the development through time of all species (or functional types) in a community. It also deals with the impacts of disturbances and seed dispersal on this development. Succession takes place within a cell without regard for the state of neighboring cells. Thus, for example, there is no competition for light between vegetation in neighboring cells. However, the successional state of a cell can affect the lateral flow of resources such as water. The following is a partial list of current succession modules:

- Markov model with transition probabilities affected by the other three modules (Horn 1981);
- Vital Attributes module (Noble and Slatyer 1980);
- FATE module (Moore and Noble 1990);
- Gap model, an individual-based model (Jabowa) (Botkin et al. 1972);
- Kohyama, another individual-based model (Kohyama 1993).

Disturbance

- Disturbance modules are essentially spread algorithms combined with a flag to indicate to the succession module what type of disturbance has affected a cell (e.g., fire, drought, or epidemic). These options will not necessarily apply to every disturbance module. It is the succession module that implements the consequences of a disturbance on a cell. There can be more than one disturbance module in any given configuration of LAMOS. For example, fire, insect herbivory, and harvesting may be combined. The following is a list of currently implemented disturbance modules.
- Three "cookie-cutter" algorithms (developed by Sandra Lavorel) in which disturbance shape is imposed around initiation cells by geometric rules that may or may not be sensitive to underlying vegetation.
- Five contagious fire-spread algorithms.
- Four types of percolation algorithms, including two from Robert Gardner (Cellular Automata model of Plant Spread [CAPS]) in which fire propagates by means of percolation rules around initiation cells. Percolation follows a single probability value and is indifferent to cell vegetation state. Fires are restarted in successive initiation cells until the quota of burned area for the year (temporally variable) is reached.
- A basic example of vegetation-sensitive percolation (developed by Sandra Lavorel and Ian Davies) in which ignition and propagation are functions of vegetation flammability and wind.
- A disturbance module (Li 1997) in which ignition and propagation are functions of time since last fire, fuel type, precipitation, and slope.
- A detailed fire process model called FIRESCAPE (Cary 1997, 1998) in which a weather engine produces daily weather, and ignition probability is linked to weather and is drawn from a spatially variable probability surface related to terrain. This model allows for fire growth based on the McArthur Forest Fire Danger Index, driven by hourly weather and modified for fuel dynamics and slope, and elliptical fire spread, with extinguishment thresholds a function of fire-line intensity.

Dispersal

Dispersal modules determine how to distribute seeds produced through the fecundity function of succession. They generate seed rain, which is then passed on to the succession module for regeneration. Each FG can use any one of the dispersal

modules. The following are some of the current dispersal modules:

- bath, in which all seeds resulting from fecundity in all of the pixels are pooled over the whole landscape and distributed evenly to all sites;
- continuous kernel, which uses an exponential distance decay function that distributes seeds around source cells;
- percolation, which distributes seeds only to nearest neighbors from a source cell (the size of the neighborhood is defined as an attribute of each FG); and
- cellular automaton, which looks for available seeds in the neighborhood of colonizable cells.

In addition to these algorithms, seed rain can be switched off altogether or confined within the source cell.

Lateral Flow

This module associates any resource with a distribution algorithm. Topography, successional state, and various global environmental variables can affect the lateral flow of material across the landscape. Currently a single module of water flow is based on TOPMODEL (Ostendorf and Reynolds 1993). Water runoff is calculated solely on the basis of topography.

Communication Between Modules

Succession acts as the communication hub for the model. Every landscape module receives information from the succession module on the state of vegetation (e.g., fuel quantity and quality, seed availability, and transpiring leaf area), which it needs to operate its specific processes. In turn, once disturbance, dispersal, and lateral flow have operated for a given time step, they return information to the succession module about how to update the vegetation state as a result of landscape processes. The methods implemented for each module set the communication needs that must be met to correctly link each method to succession. For example, many fire propagation methods need information on the amount of standing biomass and the breakup of this biomass into functional types or into different types of material (e.g., wood, leaves, and litter) to calculate flammability. Similarly, the operation of dispersal constrains succession to provide information about presence or abundance of seeds. Hence the challenge in LAMOS lies in bridging across methods implemented for different modules. Often this involves adding new functions to existing methods. For example, the Vital Attribute method for succession originally produced no information on either biomass distribution across functional types or on seed output. These were added as part when Vital Attributes was incorporated into LAMOS.

Using LAMOS for Comparative Analysis of Landscape Models

LAMOS has been tailored to meet specific objectives for research on global change effects at the landscape scale. Several challenges must be met:

- To understand and predict future disturbance regimes and their interactions with landscape vegetation patterns. Fire has been recognized as one of the most sensitive natural disturbances to climatic, atmospheric, land-use and biodiversity changes and will receive priority attention.
- To examine migration of plant species in response to climate change, in the context of landscapes fragmented by human land use and increasing disturbed habitats.
- To assess changes in biogeochemical fluxes and feedback to the atmosphere.

To answer these challenges, landscape researchers involved in Global Change Terrestrial Ecosystems have recognized the need for a formal comparison of landscape models, specifically landscape fire models and seed dispersal models, with the following aims:

- to understand how much detail in modeling methods and data is required to account for the spread and effects of disturbances (e.g., fire) and seed rain, including rare, long-distance dispersal events; and
- to carry out detailed analyses of the interactions of disturbance and dispersal with landscape spatial pattern.

LAMOS is proposed as one of the tools to support these exercises.

The knowledge base and the models derived from the comparison exercises will be applied in running simulations for scenarios of land use and climatic change in target areas representative of the range of global situations.

References

Botkin, D.B.; Janak, J.F.; Wallis, J.R. 1972. Some ecological consequences of a computer model of forest growth. J. Ecol. 60:849–872.

Cary, G.J. 1997. Analysis of the effective spatial scale of neighbourhoods with respect to fire regimes in topographically complex landscapes. Pages 434–439 *in* A.D. McDonald and M. McAleer, eds. Proc. Int. Congr. Model. Simulation, December 8–11, 1997, Hobart, Tasmania.

Cary, G.J. 1998. Predicting fire regimes and their ecological effects in spatially complex landscapes. Ph.D. thesis, Aust. Natl. Univ., Canberra, ACT, Australia.

Gardner, R.H.; Romme, W.H.; Turner, M.G. 1999. Predicting forest fire effects at landscape scales. Pages 163–185 *in* D.J. Mladenoff and W.L. Baker, eds. Spatial modelling of forest landscapes: approaches and applications. Cambridge Univ. Press, New York, NY.

Gitay, H.; Noble, I.R. 1997. What are functional types and how should we seek them? Pages 3–19 *in* Plant functional types their relevance to ecosystem properties and global change. Cambridge Univ. Press, New York, NY. International Geosphere-Biosphere Programme book series: 1.

Horn, H.S. 1975. Markovian properties of forest succession. Pages 196–211 *in* M.L. Cody and J.M. Diamond, eds. Ecology and evolution of communities. Harvard Univ. Press, Cambridge, MA.

Kohyama, T. 1993. Size-structured tree populations in gap-dynamic forest—the forest architecture hypothesis for the stable coexistence of species. J. Ecol. 81:131–143.

Li, C.; Ter-Mikaelian, M.; Pereira, A. 1997. Temporal fire disturbance patterns on a forest landscape. Ecol. Model. 99:137–150.

Moore, A.D.; Noble, I.R. 1990. An individualistic model of vegetation stand dynamics. J. Environ. Manage. 31:61–81.

Noble, I.R.; Gitay, H. 1996. A functional classification for predicting the dynamics of landscapes. J. Veg. Sci. 7:329–336.

Noble, I.R.; Slatyer, R.O. 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbance. Vegetatio 43:5–21.

Ostendorf, B.; Reynolds, J.F. 1993. Relationships between a terrain-based hydrologic model and patch scale vegetation patterns in an arctic tundra landscape. Landsc. Ecol. 8:229–237.

Rupp; T.S.; Starfield, A.M.; Chapin, F.S., III. 2000. A frame-based spatially explicit model of subarctic vegetation response to climatic change: a comparison with a point model. Landsc. Ecol.15:383–400.

Exploring the Envelope of Variation with LANDIS, a Spatially Explicit Model of Forest Disturbance and Succession

Frédérik Doyon
Institut québécois d'aménagement de la forêt feuillue
88, rue Principale, Saint-André-Avellin, Québec, Canada J0V 1W0
E-mail: fdoyon@igaff.gc.ca

As part of Millar Western Forest Products' (MWFP) forest management planning process for its forest management area (FMA) near Whitecourt, Alberta, we are developing an approach and set of models to predict the biodiversity effects of alternative forest management strategies. The Biodiversity Assessment Project is based on the principle that management interventions should be compared in the context of the range of variation under the natural disturbance regime. To provide this natural envelope of variation, we use the LANDIS model (Mladenoff et al. 1996), a spatially explicit model designed to simulate landscape change over long periods by reproducing succession and disturbance processes. This paper presents the model in terms of structure and processes modeled, how the various inputs have been prepared and parameterized to reflect the landscape dynamics in the Whitecourt area, and how the results are being used to define forest management strategies at the landscape level.

LANDIS is a stochastic model that uses both process-based and empirically based modules. It uses modular programming structure in C++ and runs with the Windows®, Windows NT®, or UNIX operating systems. Because it is raster-based, it can simulate the complex spatial process of seed dispersion. It also allows the user to aggregate and disaggregate patches for outputs on the basis of user-defined clusterings. In LANDIS, the succession module is based on the life-history traits of tree species, whereas the disturbance module is based on the size and frequency of fire and wind-throw disturbance, fuel accumulation, land-type susceptibility, and species age-class susceptibility to disturbances. Succession-related information was obtained through a literature review on the life-history traits of the tree species composing the forest landscapes of Whitecourt area. This information was then presented to experienced silviculturists at MWFP and adjusted according to their recommendations. For the disturbance-related information, land types were defined on the basis of the ecological classification of the area. Mean fire-return intervals were obtained for each land type by means of the roll-back technique. A global mean fire-return interval of 105.86 years was obtained for the whole FMA. We used the fire database of the Provincial Forest Fire Centre of Alberta to define the minimum, mean, and maximum fire size (0, 385, and 150 000 ha, respectively).

In the simulations, fire size was somewhat lower (376 ha) than the size specified by the model. The effect of roads as a barrier to fire is believed to be at the root of this difference. The proportion of the landscape being burnt every year varied significantly, from 0.5% to 1.4%. This result calls into question the ecological sustainability of using either area or volume even-flow constraints in timber management. The resulting age-class distribution also varied significantly. However, on average, more than 65% of the stands in the simulated landscape were under 90 years. Old-growth stands (>150 years) still represent 13% of the landscape. Forest planners committed to the natural-disturbance management model would need to either conserve about 15% of their working forest under a long-rotation regime or use practices retaining old-growth habitat structure elements on at least 15% of the landscape.

Reference

Mladenoff, D.J.; Host, G.E.; Boeder, J.; Crow, T.R. 1996. LANDIS: a spatial model of forest landscapes disturbance succession and management. Pages 175–180 *in* M.F. Goodchild, L.T. Steyart, and B.O. Parks, eds. GIS and environmental modelling: progress and research issues. GIS World Books, Fort Collins, CO.

Toward a Language for General Fire Modeling

Andrew Fall
School of Computing Science, Simon Fraser University
Burnaby, British Columbia, Canada V5A 1S6
E-mail: fall@cs.sfu.ca

High-level tools for fire modeling are designed to support the processes of model construction, modification, simulation, and comparison. In the absence of such tools, modelers are faced with two choices: program their model directly or parameterize a pre-existing model. Differences between a conceptual fire model and the model implemented in a program or a pre-existing model may be difficult to identify and may be based on hidden assumptions. Verifying and updating models may require changes at the implementation level, which exacerbates these problems. In addition, particular fire models are often embedded in a larger decision-support framework that may further constrain their adaptability. Even if the source code for the original system is available, understanding and modifying a program written by someone else poses many challenges. We believe that it should be possible to construct models without programming, and this has been one of the goals of SELES (the Spatially Explicit Landscape Event Simulator), a tool for building and running models of landscape dynamics.

Domain-specific modeling systems address these difficulties by supporting the development of models within a particular area of inquiry, at a level closer to the conceptual model, thereby making model implementation more accessible to domain experts. The goal of such systems is to provide a balance between the flexibility of programming and the structure and ease of using prebuilt models. Spreadsheets are a good example for the domain of bookkeeping. We propose that languages specific to the domain of fire modeling can help to overcome the problems associated with model implementation and comparison.

A key characteristic of domain-specific tools is that they focus on a framework for specifying behavior rather than a parameterization of prespecified behavior. A domain-specific language for fire modeling should be simple to learn and use, be flexible enough to specify a wide variety of model types, be capable of implementing arbitrarily complex models through successive refinement, force model assumptions to be explicit and model behavior to be transparent and clear, be efficient enough to process relatively large and complex models on commonly available hardware (e.g., desktop computers) and support reuse and adaptation of models to new circumstances. In addition, model descriptions should support the communication process, allowing nonmodelers to be involved in the model-building process and providing an environment in which diverse sources of knowledge can be integrated. Support for model communication extends the value of a modeling effort beyond the direct simulation results (Maxwell and Costanza 1997). The goals of simplicity, transparency, and communicability imply that a language should be declarative, requiring only the salient model behavior to be specified and letting the simulation engine fill in the details.

SELES was developed as a domain-specific language for the more general domain of landscape modeling (manuscript in preparation). One of the primary goals of SELES is to separate the specification of model behavior from the mechanics of its implementation on a computer. Our structured language frees landscape modelers from programming, allowing them to focus on the underlying model. At the heart of SELES is a discrete-event simulation engine that converts the high-level specification into a computer simulation of landscape change. This structured framework assists model prototyping and guides the development of a broad class of spatial landscape models. SELES models can include aspects of cellular automata (Itami 1994), percolation models (Gardner and O'Neill 1991), individual-based simulation (Dunning et al. 1995), difference equations, discrete-event simulation (de Vasconcelos and Zeigler 1993), and spatiotemporal Markov chains (Baltzer et al. 1998). Our language is sufficiently general to facilitate the construction of models that are quasicontinuous, periodic, or episodic; that are

deterministic, process-oriented, or stochastic; and in which processes may operate locally, regionally, or globally and be either spreading or nonspreading. Model specifications serve as a fairly clear description of their semantics, and thus models may be more easily verified, compared, modified, and reused.

We have applied SELES in a variety of landscape modeling scenarios in British Columbia, and have constructed fire models at meso to macro scales (cells sizes ranging from 1 to 25 ha) on landscapes with several hundred thousand cells. Implemented fire models have included purely theoretical models (Fall 1998), probabilistic models (e.g., Li et al. 1997), and models that combine empirical fire history information with fire behavior rules based on expert opinion. The level of detail required for a particular model should match the scale and goals of the modeling effort. Thus, models intended for a predictive fire behavior system are likely to be quite different from models built to explore theoretical disturbance spread or to be included in a strategic land management decision-support system.

Although SELES can be used to build a variety of fire model types, it represents only one step toward the goal of a general tool for fire modeling. Dynamic SELES models must be discrete-event simulations that operate on one or more raster layers of rectangular cells. In addition to the types of models supported by SELES, a general system for fire modeling should also support models based on different spatial data formats (e.g., hexagonal cells) and different model descriptions (e.g., differential equations). As fire research progresses and the number of models proliferates, however, I believe that a domain-specific language for fire models is essential to provide researchers and planners with the capability of implementing their own models, comparing their models with others, and adapting models to specific landscapes that may require behaviors not foreseen in the original model specification.

References

Baltzer, H.; Braun, P.; Koehler, W. 1998. Cellular automata models for vegetation dynamics. Ecol. Model. 107:113–125.

de Vasconcela, M.; Zeigler, B. 1993. Discrete-event simulation of forest landscape response to fire disturbance. Ecol. Model. 65:177–198.

Dunning, J.; Stewart. D.; Danielson, B.; Noon, B.; Root, T.; Lamberson. R.; Stevens, E. 1995. Spatially explicit population models: current forms and future uses. Ecol. Appl. 5:3–11.

Fall, J. 1998. Reconstructing the historical frequency of fire: a simulation approach to D models for landscape analysis. Pages 289–307 *in* M.G. Turner and R.H. Gardner, eds. Quantitative methods in landscape ecology. Springer-Verlag, New York, NY.

Gardner, R.H.; O'Neill, R.V. 1991 Pattern, process, and predictability: the use of neutral models for landscape analysis. Pages 280–307 *in* M.G. Turner and R.H. Gardner, eds. Quantitative methods in landscape ecology. Springer-Verlag, New York. NY.

Itami, R. 1994. Simulating spatial dynamics: cellular automata theory. Landsc. Urban Plan. 30:27–47.

Li, C.; Ter-Mikaelian, M.; Perera, A. 1997. Temporal fire disturbance patterns on a forest landscape. Ecol. Model. 99:137–150.

Maxwell, T.; Costanza, R. 1997. An open geographic modeling environment. Simulation J. 8:175–185.

Simulating Fire Regimes with FIRESCAPE

Geoffrey J. Cary
Department of Forestry, Australian National University
Canberra, ACT 0200, Australia
and
Cooperative Research Centre for Greenhouse Accounting
P.O. Box 475, Canberra, ACT 2601, Australia
E-mail: geoffrey.cary@anu.edu.au

FIRESCAPE is a process-based model for simulating fire regimes in spatially complex landscapes. The underlying philosophy of this kind of model is that an understanding of the landscape patterns of fire regimes can be obtained from a synthesis of lower-order processes relating to weather, ignition, fuel dynamics, fire spread, and extinguishment. The model has been implemented in a study region approximately 1 million ha in size in south eastern Australia.

FIRESCAPE simulates fires on an array of square 1-ha pixels. It operates on a daily time step when there are no fires burning in the landscape and on an hourly time step when there are one or more fires. For each day of the simulation, irrespective of whether a fire is burning, daily meteorological variables are synthesized from a correlative weather generator that simulates the meteorological variables required for fire danger modeling. This approach generates synthetic sequences of weather based on the stochastic structure of the meteorological process. The daily probability of lightning occurrence is determined from an empirical model that relates thunder occurrence to aspects of temperature and precipitation over 11 years of daily weather data.

Locations of lightning ignitions are modeled by an empirical relationship between lightning strike locations and two measures of the terrain. The probability of lightning ignition is positively associated with the macro-scale elevation at the broad spatial scale, which primarily reflects the orographic effect of mountain ranges on storm occurrence. It is also positively associated with the magnitude of the meso-scale elevation residual (the difference between the elevation of a site and the average elevation measured at a broader spatial scale) at finer spatial scales.

Once ignited, fires spread from pixel to pixel according to elliptical fire spread principles. The forward rate of spread is predicted by the McArthur Mk 5 Forest Fire Danger Meter. It is assumed in the version of the model presented here that there has been no clearing of forest and therefore that the meter is suitable for much of the landscape. This is not true in the real world, where there are extensive areas of grass-dominated vegetation. Fuel-load dynamics are described by Olson's simple asymptotic litter accumulation curve. Pixel-to-pixel fire spread is unsuccessful if the predicted intensity of the event is below a threshold that must be determined by the user. Each ignition, if it spreads, results in a single fire event that, when combined with other such events, defines the spatial pattern of the fire regime. At the end of a simulation, spatial patterns in interfire interval, fire-line intensity, and season of fire occurrence are determined and mapped.

Models like FIRESCAPE can be used to improve our understanding of the processes responsible for controling spatial patterns of fire regimes. The model has been used to identify the size of ignition neighborhoods (Cary 1997) and to investigate the sensitivity of fire regimes to climate change (Cary and Banks forthcoming). A new study will analyze the relationship between different approaches to hazard-reduction burning and plant-community dynamics once a more fully specified vegetation model is completed.

In this forum, the study of sensitivity in relation to climate change is of particular interest. Several studies using FIRESCAPE have indicated that fire frequency is likely to increase under a climate scenario wherein carbon dioxide is doubled, although the extent of any increase will depend on global climate sensitivity, as well as on other factors. More fires are predicted to occur in spring and

autumn under the changed climate than under the current climate. It is proposed that increases in fire frequency are more likely to be a function of a reduction in the probability of fire extinguishment than a function of significant increases in fire intensity at the other end of the fire behavior spectrum. Further, given the absence of anthropogenic fire management, including fuel management and fire suppression, actual increases in fire frequency are likely to be less than predicted. A more detailed account can be found in Cary (forthcoming).

References

Cary, G.J. 1997. Analysis of the effective spatial scale of neighbourhoods with respect to fire regimes in topographically complex landscapes. Pages 434–439 *in* A.D. McDonald and M. McAleer, eds. Proc. Int. Congr. Model. Simulation, December 8–11, 1997, Hobart, Tasmania. Model. Simulation Soc. Aust., Canberra, ACT.

Cary, G.J. n.d. Importance of a changing climate for fire regimes in Australia. *In* R. Bradstock, A.M. Gill, J.E. Williams, eds. Flammable Australia: the fire regimes and biodiversity of a continent. Cambridge Univ. Press, New York, NY. Forthcoming.

Cary, G.J.; Banks, J.C.G. n.d. Fire regime sensitivity to global climate change: an Australian perspective. *In* J.L. Innes, M.M. Verstraete, and M. Beniston, eds. Advances in global change research. Kluwer Acad. Publ., Dordrecht, The Netherlands. Forthcoming.

A Regional-Scale Fire Model for a Dynamic Global Vegetation Model

Sergey Venevsky, Kirsten Thonicke, Stephen Sitch, and Wolfgang Cramer
Potsdam Institute for Climate Impact
Telegrafenberg C4, 14412 Potsdam, Germany
E-mail: sergey@pik-potsdam.de
E-mail: thonicke@pik-potsdam.de
E-mail: sitch@pik-potsdam.de
E-mail: cramer@pik-potsdam.de

Model

A new fire model for a dynamic global vegetation model (DGVM) is proposed, which estimates areas burned on a macro-scale (10 to 100 km). The model consists of three parts: evaluating fire danger due to climatic conditions, estimating the number of fires, and estimating areas burned. The model can operate on two time steps, daily and monthly, and can interact with a DGVM, providing additional forcing for vegetation competition. Fire danger is related to the number of dry days and the amplitude of daily temperature fluctuation on those days. The number of fires on fire days varies with the human population density and their social behavior. Areas burned are calculated on the basis of average wind speed, available fuel, and fire duration. The fire model was built into the Lund-Potsdam-Jena DGVM and was tested for peninsular Spain.

Data

The climate data used in the simulation were compiled by the Carbon Cycle Model Linkage Project using monthly climate data for a 0.5° × 0.5° grid, provided by the Climate Research Unit, University of East Anglia, UK. Soil texture information was obtained from the Food an Agriculture Organization soil data set. Human population density data, also for 0.5° × 0.5° cells for the Iberian peninsula were extracted from the global population density at a 5-inch resolution. Validation of the model was based on published numbers of fires and areas burned in peninsular Spain during the period 1974–1994 (Moreno et al. 1998). These data include the geographical distribution of number of fires and areas burned for the entire period and the yearly course of number of fires and surface burned in Spain during these last decades.

Methods

The fire model was run with a monthly time step for the period 1974–1994 for the Iberian peninsula at a spatial resolution of 0.5° × 0.5°.

Results

Geographic Distribution

The simulated geographic distribution of number of fires and area burned generally reproduced the geographic pattern for the observed data (see Fig. 4, p. 167, Moreno et al. 1998). For a large proportion of peninsular Spain, there were 2–20 fires per 10 000 ha and 10 to 1 000 ha per 10 000 ha were burned over the two decades of the simulation, which coincides well with the fire statistics for the period.

The distribution of number of fires had a greater geographic variability than the distribution of areas burned, which reflects the considerable differences in climate conditions and population concentration in different regions of the country. The greatest concentrations of fires for the 20-year period (50–100 per 10 000 ha) were both simulated and observed in the coastal zone of Spain, in the provinces of Andalucia, Valencia, and Catalonia, as well as near large cities such as Madrid, Valladolid, and San Sebastian. The lowest concentrations of fires (3–9 per 10 000 ha) were simulated and observed for the Iberian System mountains, Zaragoza province, and the Pyrenees. The model underestimated the concentration of fires in Galicia province and in the Cantabrian mountains (20–50 fires per 10 000 ha in the simulation, but 50–100 per 10 000 ha observed). This underestimation is probably related to the high number of intentional ignitions in the region, initiated mainly in the early 1990s (see Fig. 5, p. 168, and Fig. 12, p. 179, Moreno et al. 1998).

The observed and simulated geographic distribution of areas burned for 1974–1994 was more even than that of number of fires, for example, in the mountainous regions of Catalonia, Valencia, and Andalucia. The vegetation pattern influences fuel composition in these regions, damping rapid spread of fires. Again, the greatest areas burned, both observed and simulated (100 to 5 000 ha), occurred in the coastal Mediterranean zone, whereas areas burned were considerably less in the northeastern part of Spain (10–500 ha). The model did not reproduce large areas that were burned in Galicia and the Cantabrian mountains because it underestimated the number of fires in these regions.

Annual Dynamics of Fires in Spain, 1974–1994

The observed total number of fires and areas burned for peninsular Spain in 1974–1994 were extracted from Moreno et al. 1998 (Table 3, p. 169) and compared with the simulated totals.

The observed and simulated numbers of fires and areas burned had similar annual dynamics. The means of number of fires and areas burned were well reproduced in the simulation. The maximum–minimum sequence was the same for the simulation and the observed data until1988, except in 1983. The increase in number of fires and areas burned occurring in the simulation for 1983 (the opposite trend to that found in the fire statistics data, was probably due to the considerable drop in monthly precipitation in Spain for this year. The temporal pattern for area burned was generally the same for the simulation and the observed data, except for 1983, 1989, and 1990.

Discussion

The suggested fire model allows investigation of fire regimes with simple assumptions about climatic and human-induced changes on different time scales for large geographic regions. Successful simulation results at monthly resolution show that it is possible to study fire–vegetation feedback using a mechanistic approach instead of stochastic modeling, which requires enormous computer resources and an unrealistic amount of high-quality input data for model parameterization. However, there is a need to include dynamic land use in a vegetation model for better performance of the fire model.

Reference

Moreno, J.M.; Vazquez, A.; Velez, R. 1998. Recent history of forest fires in Spain. Pages 159–185 *in* J.M. Moreno, ed. Large forest fires. Backhuys Publ., Leiden, The Netherlands.

Breakout Session 1
Incorporating Fire into Dynamic Global Vegetation Models

This breakout session addressed possible methods for incorporating fire into dynamic global vegetation models (DGVMs). Topics of discussion included disturbance issues, model attributes, fire modeling approaches, verification, fire–climate linkages, and errors and uncertainties.

DGVM Background

- Purpose of DGVMs is to estimate:
  - Redistribution of vegetation
  - Source and sink of carbon pools
- Spatial scales used in DGVMs:
  - Extent: continental, global
  - Grain: 10 km to 0.5°
- Temporal scales used in DGVMs:
  - Extent: centuries
  - Grain: daily to monthly

Disturbance Issues

Fire determines vegetation in many regions and ecosystems such as boreal forests, savannas, and Mediterranean landscapes. Fire results in sudden changes in carbon pools and rapid redistribution of vegetation. Current fire models operate at a variety of spatial and temporal scales. The choice of which approach is used is essentially an issue of scale.

Model Attributes

What are the key attributes of a model that includes fire *effects* in a DGVM?

- Vegetation represented by plant functional types
- A single cell may have multiple vegetation types
- Assumption of homogeneity (nonspatial) within cell
- Spatial effects of fires *diluted* by cell homogeneity
- Fire events remove biomass from cell depending on area burned
- Biomass size distributions (fuels) calculated to estimate correct fire-return time

Approaches for Including Fire in DGVMs

Are multiple approaches possible?

- Statistical approaches
  - Intrinsic effects may be included in statistical approaches
- Process-based approach for fire modeling
  - Physical-based equations (e.g., fuel moisture)
  - Feedback between fuels and fire
- New methods: stochastic, epidemic (and possibly other emergent approaches)

Verification of Approach

What is needed to satisfy the scientific community?

- Acceptable fire regime under current climate and weather
  - Change in fire regime with change in climate
  - Climate-related ignition (Are there differences in ignition in limited versus unlimited systems?)
- Spectrum of effects (intensities) and fire sizes within cells
  - Subcell information about fires matches known regimes
- Demonstrated validity of functional types to respond to fire

Climate–Fire Linkages as Tests

What tests are desirable (and possible)?

- Tests against historical trends
  - Eastern Canadian trend of declines in fire danger and initiation of fires
  - Match to paleologic records (with and without fire)
- Partnership with empirical studies of climate and fire records (especially those free of suppression effects)
- Relationship between fires and changing El Niño Southern Oscillation patterns
- Effect of present climate regime on vegetation pattern

Errors and Uncertainties

- Biases
  - Sources of bias can be regionally identifiable
- Uncertainties
  - Is it possible to calculate confidence intervals via multiple data sets?
  - Will model comparisons suffice?

Breakout Session 2
Gaps and Information Needs in Fire Models

This breakout session addressed modeling gaps and information needs for fire models. Topics included fire behavior, ecological effects, and some general aspects, including interactions between fire and land use and validation.

Fire Behavior

- Additional information and improved models are required for the following aspects:
  - Spotting
  - Crowning
  - Fuel
    - Inventory conversion of fuel types (particularly important in USA)
    - Inventory quality
    - Fuel characterization
    - Fuel buildup
  - Extinguishment
- Improved ignition models are required to address the following aspects:
  - Location of fires
  - Number of fires
  - Human and natural causes
- Weather and climate aspects with respect to fire behavior:
  - Diurnal effects
  - Seasonality
- Fire islands

  Currently, fire islands (unburned regions within a fire perimeter) are not well modeled. More information on causes is required, including the following:
  - Time of day burned
  - Topographic and other fuel breaks

Ecological Effects

- Seasonality effects (e.g., regeneration)
- Weather after fire (and its effect on regeneration)
- Mortality and its influences on the amount and timing of seed fall
- Succession modeling. Despite the large number of succession models available, opinion is still divided regarding their adequacy
- Interactions of fire, insect attack, and disease require additional information and modeling efforts

General

- Land-use interactions and their influence on fire growth and subsequent regeneration:
  - Grazing
  - Alien plants and animals
  - Salvage logging
  - Planting and tending
- Economic models not integrated at all with fire models
- Insurance modeling with respect to fire is required (e.g., rural homes and businesses)
- Develop links and multipurpose models to deal with the multiple objectives of land managers, including hazards, recreation, and wildlife.
- Fire models:
  - Validation needed
  - Standard test data needed
  - Intramodel comparisons needed
  - Computer technology problems must be addressed
    - Bigger models (brute force)
    - Smaller models (faster)
    - Parallel processing

Breakout Session 3
Application of Fire Models with Respect to Forest and Vegetation Management

This breakout session addressed the application of fire models with respect to forest and vegetation management. Management objectives include biodiversity (wildlife), ecosystem structure and function, timber supply, and carbon. The intent was to focus discussions on the following three questions:

1. Are the fire models appropriate for their intended application? If not, where are the problems? For example, fire behavior and occurrence models used not appropriate for scale of simulation (e.g., using FBP/BEHAVE at the most coarse scale) or succession models used not appropriate for scale of simulation (e.g., using stand-level succession and tree growth models at the most coarse scale).

2. How important is it to model other disturbances (e.g., insects, disease, wind throw, harvesting) in addition to fire and the interaction between disturbances? How best can these be incorporated into landscape fire models?

3. How can landscape fire modeling best be incorporated into land management planning? Which models would be appropriate for scenario planning activities?

The facilitator of this breakout session chose role playing to initiate and promote discussion. The facilitator took the role of a manager–superintendent of a forest area or park. The participants were then challenged to justify to the manager why landscape fire models are required (i.e., what is the application of fire models with respect to forest and vegetation management?).

Despite the broad scope of the question and the limited time available, each group generated considerable discussion. The following list highlights the main items discussed during this breakout session.

Need to Incorporate Fire into Planning

The positive and negative effects of fire need to be understood and recognized in support of land management planning. Ecosystems are in constant flux. In fire-dependent ecosystems, fire is the predominant agent of change. Fire therefore needs to be incorporated into planning.

Need to Better Understand Fire as a Process

A landscape fire model should not be used to produce a single number. Such models should be used to provide insights and to gain a better understanding of the probable range of output. Probabilities and distributions are better outputs than a single model run and output.

Landscape fire models can help land managers to better understand fire as process. These models can spatially show relative differences in fire regime characteristics.

Range of Variability

Managing landscapes within a range of variability is considered more ecologically and operationally sound than managing landscapes to achieve one static target. Landscape fire models are particularly useful for gaining insights about the confidence bands associated with the variability being managed.

Sensitivity Analysis: Evaluating Scenarios

Landscape fire models are useful for evaluating different scenarios. What does the forest landscape look like in 50 or 100 years? Are these landscapes more or less susceptible to fire?

Need to Define Target or Direction

Land managers need to clearly define the desired landscape they plan to manage. Landscape fire models can be used to validate landscape management objectives and targets for attaining specific landscape metrics. This is important if fire is a process controlling age-class distribution, patch characteristics, overall landscape mosaic, and species composition.

Researchers and model developers often do not use an integrated, interdisciplinary team approach to incorporate and link operational needs. This may limit the utility of their models.

Do We Want to Emulate Historical Fire Regimes?

We cannot mimic fire in managed landscapes. We can, however, learn from fire and try to get "closer" to it. Future managed landscapes that approximate the stand and landscape structures created by natural disturbance events will improve forest health and conserve biodiversity. The problem remains in defining the term "natural" and emulating natural disturbance. To manage structure, you must understand process. You may have a structure that looks like a house but does not function as a house. Likewise, you may have a landscape that looks like a forest but does not function as a forest.

Land managers are increasingly concerned about the "naturalness" of forests and landscapes where fire control policies have affected the ecological role of fire. Fire-dependent forests that have "skipped" one or more fire cycles are considered unnatural. Relatively effective suppression activities, particularly in fire-dependent ecosystems with a historical fire regime of low- to moderate-intensity fires, have altered the forests. Increased fuel loading, increased vertical fuel continuity, species composition changes, and loss of mosaic and fuel breaks all occur.

Future fire regimes may not be the same as historical ones. Fire is a process that changes as the fire environment changes. Some agencies strive to restore ecosystems by applying prescribed fire as a management tool to emulate historical fire regimes. On landscapes where values at risk are minimal and natural processes are allowed to occur with minimal interference from humans, wildfire can play a more natural and ecological role. There is considerable debate about the need to manage the effects of fire. If large, high-intensity fires occur outside the historical range of variability, the resulting high-severity fire effects (site productivity, soil erosion) may not be desirable.

Is One Model Sufficient?

There was consensus that the use of only one landscape fire model may limit the insights and understanding of model outputs. In some cases, the results may even be misleading. Each model has its strengths and weaknesses. Land managers need to understand the assumptions and limitations of each model. They should also consider applying several different models to compare results.

Model developers would also benefit by applying their model to more than one database (i.e., study area).

Nontimber Values

Life, property, and resources are the main priorities of most fire-suppression agencies. Outside of protected areas, timber values are usually the predominant resource value protected from fire. There is a need to incorporate nontimber values in an economic assessment of the value of fire suppression. This includes nontimber market values and nonmarket values (use and non-use). Fire management agencies are increasingly being asked to justify their expenditures for fire suppression. This is often referred to as "return on investment." Which fires should receive suppression resources? When are we spending too much money?

User Friendly, Easy to Apply, Easy to Interpret

Landscape fire models will be more successful if they are user friendly, easy to apply, and easy to interpret.

Linkages to Timber Supply Models

There is a need to develop stronger linkages between landscape fire models and timber supply models. This is particularly important if fire and harvesting are competing processes in fire-dependent forests.

Timber supply models can consider wildfire threat by sequencing and preblocking stands that have the highest susceptibility to crown fire. The forest-level impact of fire can also be assessed by applying fire (i.e., uncertainty) randomly or strategically on the landscape. This allows forest management planners the opportunity to evaluate the forest exposure and potential loss due to the uncertainty of fire. This risk assessment can be used to evaluate various forest landscape designs over time and space. Which future forests best mitigate the threat of wildfire, while still recognizing the ecological role and positive effects of fire?

Landscape fire models attempt to explain the dynamics between fire as a process and the

subsequent pattern and mosaic created on the landscape. Timber supply models, by comparison, focus on stands and corresponding yields.

Effort to Implement Models

Documentation and training are important components to consider when incorporating landscape fire modeling into land management. Not all landscape fire models include appropriate algorithms and submodels for their intended application. This is particular evident when inappropriate simulation scales are used. Often, the choice of algorithms and submodels, level of detail of the data, scale of simulation, and intended outputs are not appropriately aligned to generate the best results.

Breakout Session 4
Questions for Future Landscape Fire Models

Questions Should Determine What Models Are Needed

The questions forest and fire mangers and policymakers ask will determine modeling objectives. Future landscape fire models will address a variety of topics and issues:

- climate change
- land-use change
- interactions among and feedbacks from processes
- sustainable forest management

What Does the Future Hold for Landscape Fire Models?

What will fire models look like?

What will be the role of fire in land and forest management planning?

What key fire models will be needed for the use of fire in forest management and in determining management options?

What kind of fire models will be needed for the Kyoto protocol (in terms of criteria and indicators)?

What kind of landscape fire models will be needed in park management?

Models for Climate Change

How can we capture the most important features that will permit models to predict the effects of climate change? Climate change will affect vegetation at large spatial scales, but current fire models are too local to work at that scale.

Statistical versus Process-Based Models

Cross-validation of these two types of models under present conditions is needed. What is the value of historical records for this task? There is a need to secure historical data that could be used in this validation before it is lost forever.

Can statistical models be improved by including climatic covariables?

Are process-based models the only way to model climate change? If so, what level of complexity is needed? Can these models handle conditions outside the natural range of variation, including extreme climatic events?

Climate Data

Spatial down-scaling of the global circulation climate change models is required, but will the information available allow landscape fire modeling?

For example, fire ignition (lightning-caused fires) and fire size are important unknowns. Will climate change models be able to predict factors (e.g. cold fronts, upper blocking ridges) that influence weather phenomena that in turn affect ignition and spread?

Another example would be the ability to predict fire extinguishment events using the climate change models.

Kyoto Protocol

Fire models are needed to predict carbon stocks and fluxes. Are the models currently used adequate to this task?

In the Kyoto process "natural" areas (and the role of fire in ecosystems) should not be sacrificed in the accounting game to meet carbon targets.

Land-Use Change

There is a need to include the whole range of disturbance types (e.g. insects, disease, fire, windthrow) in landscape fire modeling and a need to see how these disturbances change with land use. Disturbance regimes change in terms of a variety of factors:

- natural versus human-caused
- changes in human population densities and priorities
- interactions between disturbance types
- interaction with climate

Overarching Model Issues

There is a need for formal comparisons of landscape fire models. Such comparisons would require:

- good test data sets
- qualification of conditions of applicability

Flexibility is needed for changing questions and moving targets. This would require multiple models, but a common language.

"Get the vegetation right, and you will get everything right." An understanding of vegetation changes on the landscape is needed to infer effects on other features (e.g., wildlife).

Models are no good in the absence of the science. There is a need to know the interactions between fire and climate at the landscape scale. We need new knowledge, but we are not necessarily doing the research that tells us how systems work.

Management Options

Managers need decision support, not decisions.

A set of models are needed for forest managers, and other models are needed for research purposes.

Critical needs include gaining acceptance for these models. To ensure this, attention must be given to the following areas:

- education and transfer
- delivery of models to users in a timely fashion
- tuning the outputs to the audience
- sensitivity analysis approach

Models for fire events versus models for strategic planning: these models differ but have some similarities (i.e., common threads) in their development and capabilities.

Summary

The objective of this workshop was to explore opportunities and limitations of landscape fire models for boreal and temperate ecosystems. Goals included identification of modeling gaps and needs, incorporation of fire into dynamic global vegetation models, application of fire models for forest and vegetation management, and attempts to identify future research and management requirements.

We hope that this workshop created opportunities for people to work together on some of the issues that were raised. We need to continue to share information and ideas to foster creativity and generate knowledge, and we need to collaborate to develop tools for evaluating alternatives and providing insights useful to decision makers.

We thank our sponsors, the Canadian Forest Service, the Climate Change Action Fund and the Global Change Terrestrial Ecosystems Programme. Finally, we thank all the speakers, facilitators, rapporteurs, participants, and our hosts at the Pacific Forestry Centre.

The PowerPoint® presentations for most of the talks are available on the Internet at

<http://nofc.cfs.nrcan.gc.ca/fire/frn/English/frames.htm>

Landscape Fire Modeling Workshop
November 15–16, 1999
Participant List

Paul Addison
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: paddison@pfc.forestry.ca

Kerry Anderson
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: kanderso@nrcan.gc.ca

David W. Andison
Bandaloop Landscape Ecosystem Services
30 Debra Ann Road
Golden CO 80403
USA
E-mail: Andison@AOL.com

Judi Beck
Forest Protection Branch
BC Ministry of Forests
2nd Floor, Building A
2957 Jutland Road
Victoria BC V8W 9C1
CANADA
E-mail: Judi.Beck@gems6.gov.bc.ca

Richard Betts
Hadley Centre for Climate Prediction and Research
Meteorological Office
Bracknell
Berkshire RG12 2SY
UK
E-mail: rabetts@meto.gov.uk

Pal Bhogal
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: pbhogal@pfc.forestry.ca

Geoffrey J. Cary
Department of Forestry
Australian National University
Canberra ACT 0200
AUSTRALIA
E-mail: geoffrey.cary@anu.edu.au

Ian Corns
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: icorns@nrcan.gc.ca

Steve Cumming
Boreal Ecosystems Research Ltd.
6915 – 106 Street
Edmonton AB T6H 2W1
CANADA
E-mail: stevec@berl.ab.ca

George Dalrymple
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: gdalrymple@pfc.forestry.ca

Ian D. Davies
Ecosystem Dynamics Group
Research School of Biological Sciences
Institute of Advanced Sciences
Australian National University
Canberra ACT 0200
AUSTRALIA
E-mail: ian.davies@anu.edu.au

Bill de Groot
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: bdegroot@nrcan.gc.ca

Craig Delong
BC Ministry of Forests
Prince George Forest Region
1011 4th Avenue
Prince George BC V2L 3H9
CANADA
E-mail: craig.delong@gems1.gov.bc.ca

Frédérik Doyon
Institut québécois d'aménagement
de la forêt feuillue
88, rue Principale
Saint-André-Avellin QC J0V 1W0
CANADA
E-mail: fdoyon@igaff.gc.ca

Andrew Fall
School of Computing Science
Simon Fraser University
Burnaby BC V5A 1S6
CANADA
E-mail: fall@cs.sfu.ca

Joseph Fall
School of Resource and
Environmental Management
Simon Fraser University
Burnaby BC V5A 1S6
CANADA
E-mail: jfall@sfu.ca

Mark A. Finney
USDA Forest Service
Rocky Mountain Research Station
Fire Sciences Laboratory
PO Box 8089
Missoula MT 59807
USA
E-mail: mfinney@fs.fed.us

Mike Flannigan
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: mflannig@nrcan.gc.ca

Robert H. Gardner
Appalachian Environmental Laboratory
University of Maryland Center
for Environmental Studies
301 Braddock Road
Frostburg MD 21532
USA
E-mail: gardner@al.umces.edu

Sylvie Gauthier
Canadian Forest Service
Laurentian Forestry Centre
1055, rue du P.E.P.S.
PO Box 3800
Sainte-Foy QC G1V 4C7
CANADA
E-mail: sgauthier@cfl.forestry.ca

Brad Hawkes
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: bhawkes@pfc.forestry.ca

Fangliang He
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: fhe@pfc.forestry.ca

Steve Higgins
National Botanical Institute
Private Bag
Claremont 7735
SOUTH AFRICA
E-mail: higgins@nbict.nbi.ac.za

Kelvin Hirsch
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: khirsch@nrcan.gc.ca

Victor Kafka
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: vkafka@nrcan.gc.ca

Bob Keane
USDA Forest Service
Rocky Mountain Research Station
Fire Sciences Laboratory
PO Box 8089
Missoula MT 59807
USA
E-mail: rkeane@fs.fed.us

Werner Kurz
ESSA Technologies Ltd.
1765 West 8th Avenue
Vancouver BC V6J 5C6
CANADA
E-mail: wkurz@essa.com

Sandra Lavorel
Centre d'écologie fonctionnelle et évolutive
Centre national de la recherche
scientifique UPR 9056
1919, route de Mende
34293 Montpellier Cedex 05
FRANCE
E-mail: lavorel@cefe.cnrs-mop.fr

James M. Lenihan
Forest Sciences Laboratory
3200 SW Jefferson Way
Corvallis OR 97331
USA
E-mail: lenihan@fsl.orst.edu

Chao Li
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: cli@nrcan.gc.ca

Tim Lynham
Canadian Forest Service
Great Lakes Forestry Centre
PO Box 490
Sault Ste Marie ON P6A 5M7
CANADA
E-mail: tlynham@nrcan.gc.ca

David L. Martell
Faculty of Forestry
University of Toronto
Toronto ON M5S 3B3
CANADA
E-mail: martell@smokey.forestry.utoronto.ca

Rob McAlpine
Ontario Ministry of Natural Resources
70 Foster Drive, Suite 400
Sault Ste Marie ON P6A 6V5
CANADA
E-mail: rob.mcalpine@mnr.gov.on.ca

Doug McRae
Canadian Forest Service
Great Lakes Forestry Centre
PO Box 490
Sault Ste Marie ON P6A 5M7
CANADA
E-mail: dmcrae@nrcan.gc.ca

Andrew Mitchell
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: anmitche@pfc.forestry.ca

Ronald P. Neilson
USDA Forest Service
Forest Sciences Laboratory
3200 SW Jefferson Way
Corvallis OR 97331
USA
E-mail: neilson@fsl.orst.edu

Robin Quenet
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: rquenet@pfc.forestry.ca

John Parminter
Research Branch
BC Ministry of Forests
PO Box 9519, Station Provincial Government
Victoria BC V8W 9C2
CANADA
E-mail: john.parminter@gems7.gov.bc.ca

Juli Pausas
Centro de Estudios Ambientales del Mediterraneo
Parc Tecnologic
C/C.R. Darwin 14
46980 Paterna, Valencia
SPAIN
E-mail: juli@ceam.es

Scott Rupp
Forest Soils Laboratory
University of Alaska
Fairbanks AK 99775
USA
E-mail: srupp@merlin.salrm.uaf.edu

Brian Stocks
Canadian Forest Service
Great Lakes Forestry Centre
PO Box 490
Sault Ste Marie ON P6A 5M7
CANADA
E-mail: bstocks@nrcan.gc.ca

Roger Suffling
School of Planning
University of Waterloo
Waterloo ON N2L 3G1
CANADA
E-mail: rcsuffli@cousteau.uwaterloo.ca

Steve Taylor
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: staylor@pfc.forestry.ca

Bernie Todd
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: btodd@nrcan.gc.ca

Cordy Tymstra
Fire Management Planning
Forest Protection Division
Alberta Land and Forest Service
10th Floor, 9920 – 108 Street
Edmonton AB T5K 2M4
CANADA
E-mail: Cordy.Tymstra@gov.ab.ca

Sergey Venevsky
Potsdam Institute for Climate Impact
Telegrafenberg C4
14412 Potsdam
GERMANY
E-mail: sergey@pik-potsdam.de

David Wallin
Center for Environmental Science
Western Washington University
Bellingham WA 98225-9181
USA
E-mail: wallin@cc.wwu.edu

Doyle Wells
Canadian Forest Service
Atlantic Region, Corner Brook Office
PO Box 960
Corner Brook NF A2H 6J3
CANADA
E-mail: dwells@nrcan.gc.ca

Dwight Scott Wolfe
McGregor Model Forest
PO Box 9000
Prince George BC V2L 4W2
CANADA
E-mail: dwight@mcgregor.bc.ca

Jim Wood
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: jwood@pfc.forestry.ca

Mike Wotton
Canadian Forest Service
Great Lakes Forestry Centre
PO Box 490
Sault Ste Marie ON P6A 5M7
CANADA
E-mail: mwotton@nrcan.gc.ca